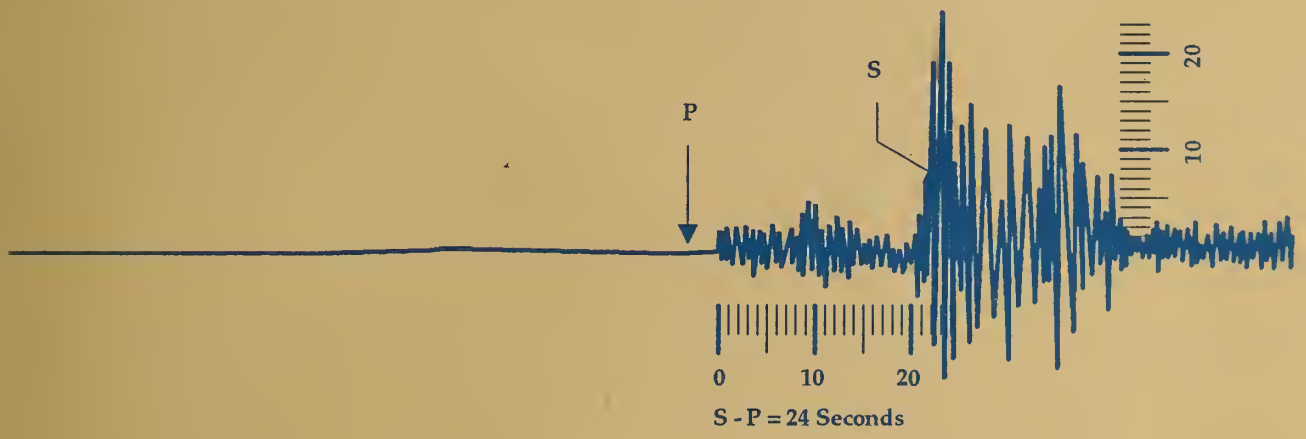
REVIEW OF SEISMIC INFORMATION

San Francisco Department of City Planning
February 1992



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Community Safety Element
of the San Francisco Master Plan
BACKGROUND REPORT 1

REVIEW OF SEISMIC INFORMATION

February 1992

San Francisco Department of City Planning

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INTRODUCTION

This is the first of three reports providing background information to be used by the City Planning Commission to review and update the Community Safety Element of the San Francisco Master Plan.

This report is a review and summary of available information about the earthquake risks facing San Francisco. Sources include geologic and seismic studies, estimates of the likely consequences on San Francisco of a major earthquake in the region, and reports following the 1989 Loma Prieta earthquake and other earthquakes. Only a small amount of the information in these books and reports could be included. Interested readers are encouraged to consult the original sources. They are listed at the end of this report and are available at the Department of City Planning. Many are also available at the San Francisco Public Library.

The other two background reports are now being prepared. Report 2 will describe current relevant policies and programs at the city, regional, state and federal levels, as well as private efforts. It will be based, as much as possible, on interviews with those responsible for safety programs. Report 3 will explore potential policies and programs which have been proposed by researchers, officials or others, and ideas which have been implemented elsewhere. The advantages and disadvantages of various approaches to safety policy, and their possible applicability to San Francisco will be examined.

Based on the information in these background reports, and any other relevant information, the department will prepare a Draft Community Safety Element for review by the public and the City Planning Commission. That document will contain proposed policies for inclusion in the Master Plan. A draft program document, describing ways to implement the proposed policies will also be prepared. The City Planning Commission will receive public testimony, and advice from its Citizens Advisory Committee, on these issues. After the draft element has been revised to the satisfaction of the City Planning Commission, the Commission will adopt the element as part of the San Francisco Master Plan.

If you would like to be notified of the availability of future background reports and other documents, and of City Planning Commission hearings on the Community Safety Element, please call or write: Catherine Bauman, Department of City Planning, 450 McAllister Street, San Francisco, CA 94102, (415) 558-6287.

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Figure 1. Damage in San Francisco from the 1865 Earthquake.
Photo: Bancroft Archives, BAREPP

Figure 2. Damage in San Francisco from the 1868 Earthquake.
Photo: San Francisco Archives, San Francisco Public Library

EARTHQUAKES IN SAN FRANCISCO

Earthquakes have always occurred in the San Francisco area and will continue to occur in the future. There is an historical record of damaging earthquakes dating as far back as 1808, when an earthquake estimated at magnitude 6 occurred. A magnitude 6 ¾ earthquake on the Hayward fault in 1836 and a magnitude 7 earthquake on the San Andreas fault in 1838 (which damaged Mission Dolores and buildings at the Presidio) occurred before there was a substantial population or many buildings to sustain damage. An 1868 Hayward fault earthquake was known as the "great San Francisco earthquake" until 1906. Damaging earthquakes of which we have historical records (usually those with a magnitude over 6) are listed in Table 1 and shown graphically in Figure 3.

These earthquakes have not, however, been evenly distributed over time. Magnitude 6 to 7 earthquakes were more frequent in the years leading up to 1906 than in the time since then. In the 70 years after the great 1906 earthquake, there have been few magnitude 6 or greater earthquakes, because a large amount of pent-up energy on the fault had been relieved. Earthquake frequencies since 1979 may represent a return to the higher rates of activity recorded before 1906.

TABLE 1 - LARGE HISTORIC EARTHQUAKES IN THE BAY AREA

Date	Location	Magnitude	Damage (in earthquake year dollars)
1808	San Francisco Region	6?	Presidio buildings damaged
1836	Hayward Fault	6 3/4	Damage in East, South Bay
1838	San Francisco Peninsula	7	Mission, Presidio damaged
1858	San Francisco Peninsula	5 3/4	Brick walls cracked in S.F.
1858	San Jose Region	6 1/4	Building damage in S.F.
1864	Southern Santa Cruz Mountains	6	Building damage in Monterey
1864	East of S.F. Bay	5 3/4	Walls considerably cracked in S.F.
1865	Southern Santa Cruz Mountains	6 1/2	Damage to City Hall and South of Market
1868	Hayward Fault	7	730 deaths, much building damage
1868	Santa Cruz Mountains	6	Walls cracked, plaster fell in S.F.
1889	Antioch	6 1/4	Damage in East Bay
1898	Mendocino	6 1/2	Damage on North Coast
1899	Morgan Hill	5 3/4	Damage in East Bay, Monterey
1906	Great 1906 earthquake	8 1/4	3000 deaths, severe damage
1911	Calaveras Fault	6.5	Damage in San Jose, Gilroy, Morgan Hill
1957	Daly City	5.7	Over $1 million damage
1969	Santa Rosa	5.7	$30 million damage in North Bay
1979	Coyote Lake	5.7	16 injuries, $500,000 damage
1980	Livermore	5.8	50 injuries, $11.5 million damage
1984	Morgan Hill	6.1	$3 million damage
1989	Loma Prieta	7.1	62 deaths, $6 billion damage

Sources: Ellsworth, William L., "Earthquake History 1769-1989," in U.S. Geological Survey, *The San Andreas Fault System, California*, Professional Paper 1515, 1990; Toppozada, et al., *Preparation of Isoseismal Maps and Summaries of Reported Effects for Pre-1900 California Earthquakes*, California Division of Mines and Geology, 1981; Bolt, Bruce, *Earthquakes*, W.H. Freeman & Co, N.Y., 1988; and Department of City Planning.

The magnitude of earthquakes which occurred before modern instruments were available is estimated based on records of damage and eyewitness accounts. These estimates are customarily expressed in fractions. Earthquakes measured with instruments are described in decimal notation.

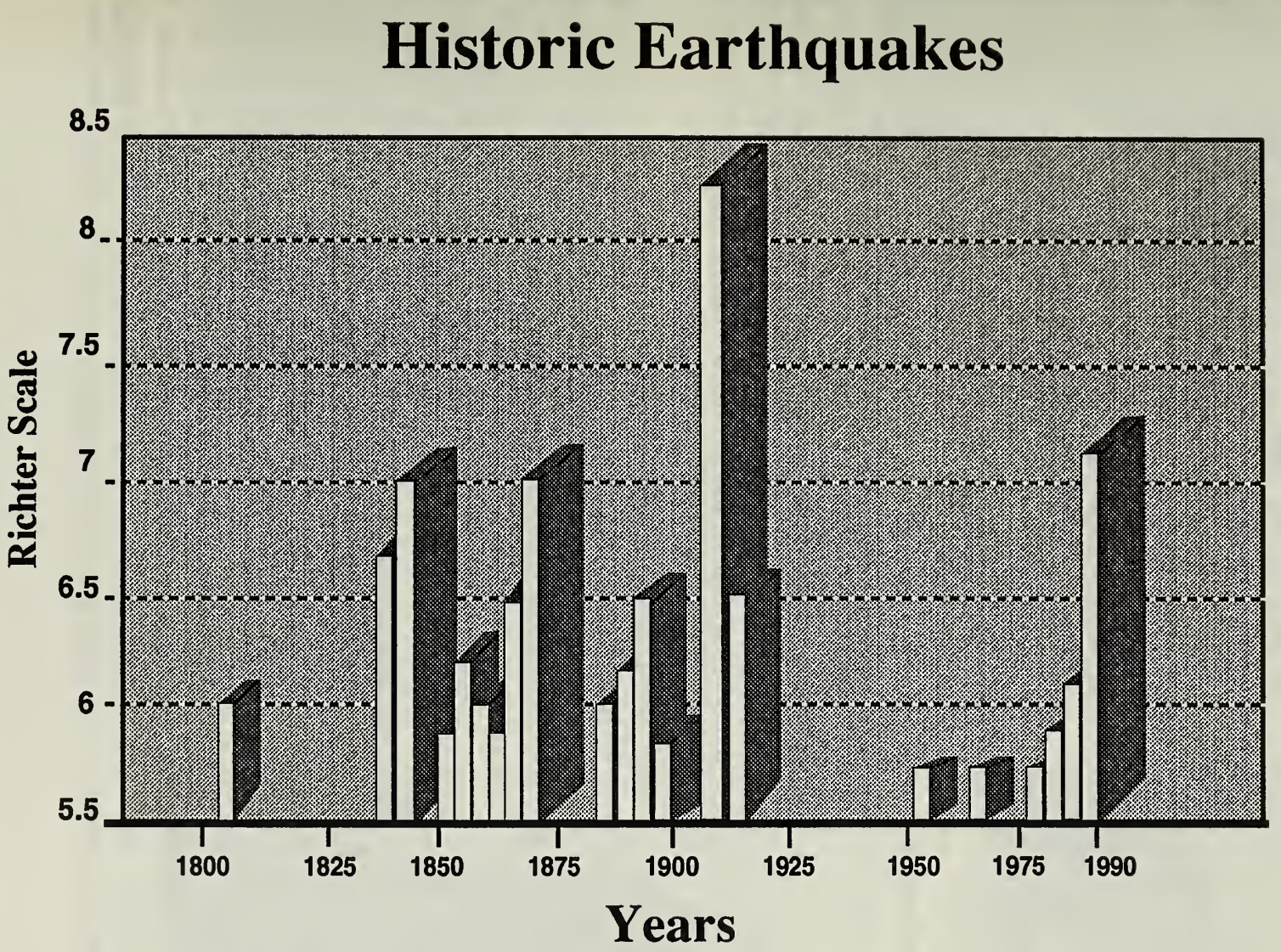


Figure 3. Historic Earthquakes in the Bay Area.

The Great 1906 San Francisco Earthquake

Figure 4. 1906 San Francisco Earthquake.
Photo: San Francisco Archives, San Francisco Public Library

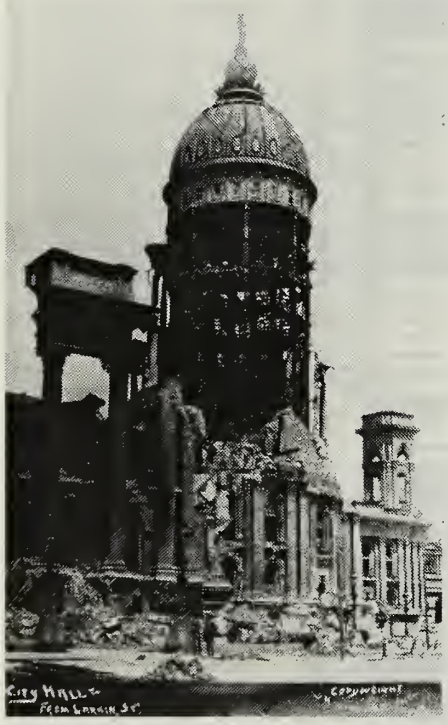


Figure 5. 1906 San Francisco Earthquake.
Photo: San Francisco Archives, San Francisco Public Library

The April 18, 1906 earthquake had a magnitude of 8¼. It was centered off of Point Reyes, northwest of San Francisco. The earthquake was followed by a large fire, making it difficult to separate earthquake destruction from fire damage. About 26 aftershocks were felt the same day. Original reports were that 700-800 people died in the earthquake and fire (out of a total population of about 400,000). Recent research shows that number to be larger, perhaps as high as 3,000. The worst building damage occurred on "made land": artificially filled areas created on former marshes, streams and bay. The wood-frame buildings in the South of Market area and brick buildings downtown were especially heavily damaged. Some buildings with steel frame or reinforced concrete structural systems and with pile foundations (including the Ferry building, the Flood building, the St. Francis Hotel), and some high quality unreinforced masonry buildings survived the earthquake with substantial but repairable damage. Others, including the City Hall, did not.

Large ground displacements in the filled ground along the Bay damaged utilities. Damage to the gas generating and distribution system resulted in explosions and exacerbated the spread of fire. Breaks in the underground water pipes resulted in a loss of fire-fighting capability. These factors contributed to the disastrous fire which followed the earthquake. Over 28,000 buildings within a four square mile area, including most of the area east of Van Ness Avenue and north of Townsend Street, were destroyed over a period of three days. About 100,000 people were left homeless. Refugee camps in parks and other open spaces continued for many months. A 1908 estimate of private property damage in the fire zone was $1 billion. This did not include earthquake damage outside of the fire zone or damage to public structures and infrastructure. Some of the municipal bonds which financed the rebuilding of public facilities were not paid off until the 1980s.

The 1989 Loma Prieta Earthquake

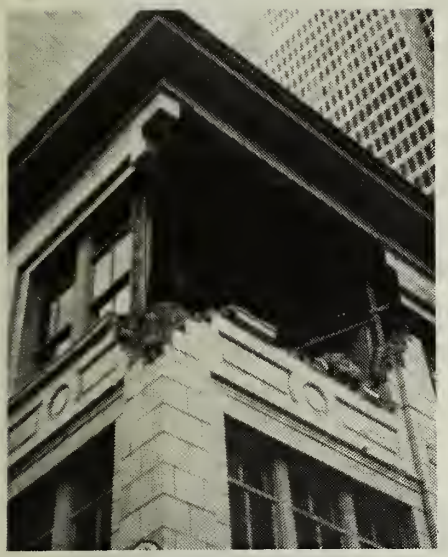


Figure 6. Damage in San Francisco from the 1989 Loma Prieta Earthquake.
Photo: Bay Area Earthquake Preparedness Project

The October 17, 1989 Loma Prieta earthquake occurred on the San Andreas fault about 60 miles (100 km) southeast of San Francisco. It had a magnitude of 7.1. Sixty-two people were killed, including eleven in San Francisco. Forty-two of these fatalities occurred because of failures of bridges and freeways. Most of the remaining deaths resulted from the collapse of buildings in Santa Cruz and San Francisco.

The total damage to private and public facilities throughout the region is estimated at over six billion dollars. The damage in San Francisco was not evenly distributed through the city. Most of the severe damage occurred in areas built on unengineered artificial fill in the Marina and South of Market district where the nature of the soils resulted in liquefaction and severe ground shaking. Many of the buildings severely damaged by the earthquake had structural weaknesses which were known to make them vulnerable to earthquake damage. They included buildings with "soft stories" (large openings and inadequate strength at the ground story) and unreinforced masonry buildings. The damaged freeways were generally located in areas of soft soil, and were built prior to 1971 when Caltrans construction standards were changed in response to the San Fernando earthquake, in which freeways failed.

Figure 7. Damage in San Francisco from the 1989 Loma Prieta Earthquake.
Photo: ©1989 Neil Hart

About 130 buildings in San Francisco, containing over 1,000 housing units, were destroyed or irreparably damaged. Many times this number of units were damaged, but have been or will be repaired. Many could not be occupied for an extended length of time while repairs were carried out. These units housed disproportionate numbers of low income residents. Additional residents were displaced by a lack of utilities. The Red Cross provided overnight shelter for about 1,100 people on the night of the earthquake. Many more displaced people undoubtedly stayed with friends or relatives instead of Red Cross shelters.

The transportation and utility systems serving San Francisco were disrupted. Many parts of the city were without electricity in the hours and days following the earthquake. Areas where ground failure damaged underground utilities were without gas service for up to 30 days while repairs were carried out. While transit systems, notably BART, were able to resume service soon after the earthquake, the freeway and bridge systems remained crippled for considerably longer. The Bay Bridge remained closed to traffic for one month. Some portions of the freeway system have not been repaired or replaced two years after the earthquake.

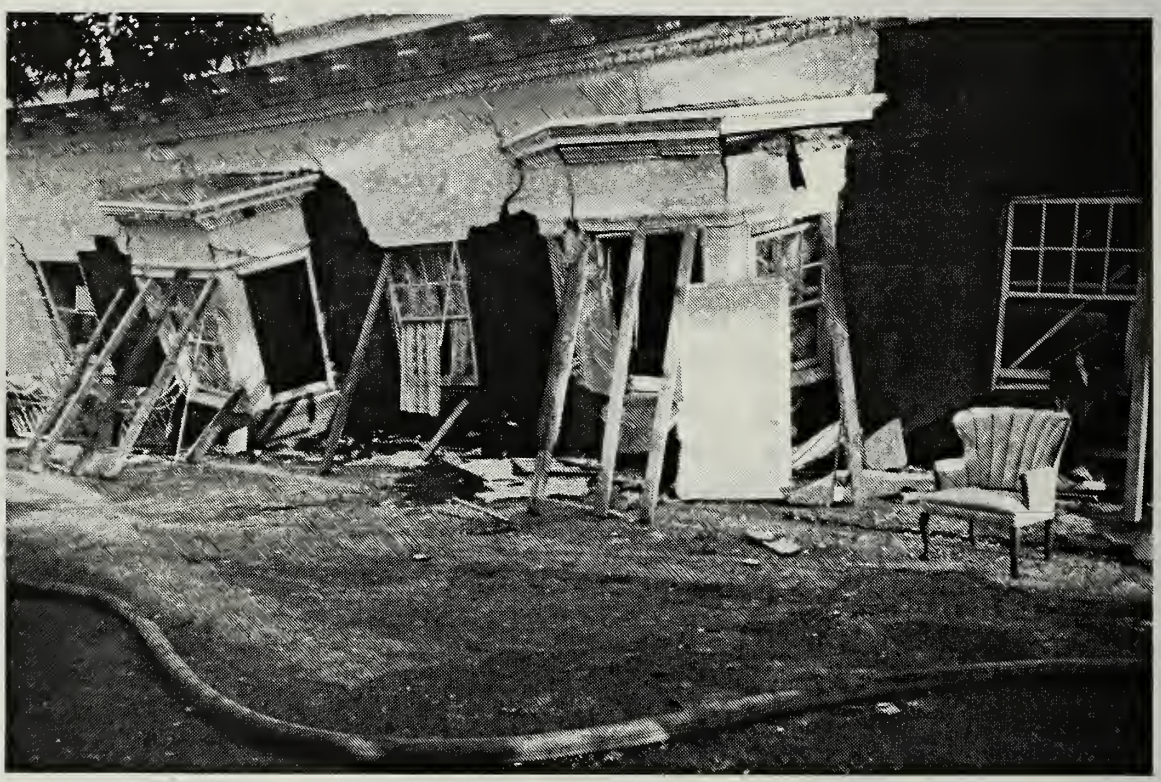
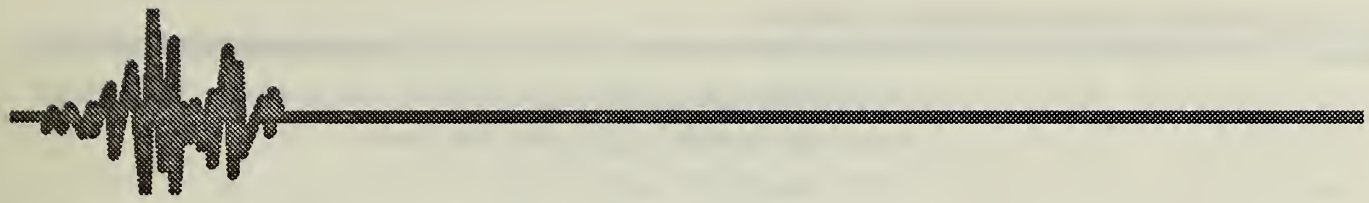


Figure 8. Damage in San Francisco from the 1989 Loma Prieta Earthquake.
Photo: ©1989 Neil Hart



PROBABILITIES OF FUTURE EARTHQUAKES

After the October 1989 Loma Prieta Earthquake, the National Earthquake Prediction Evaluation Council formed a Working Group of earthquake scientists from the U.S. Geological Survey, private industry, and academia to explore the probabilities of large earthquakes in the Bay Area, taking the most recent information into account. The Group's results were published in 1990, *Probabilities of Large Earthquakes in the San Francisco Bay Region, California*, U.S. Geological Survey Circular 1053.

Both its earthquake history and geology show that future damaging earthquakes are inevitable in the San Francisco Bay Area.

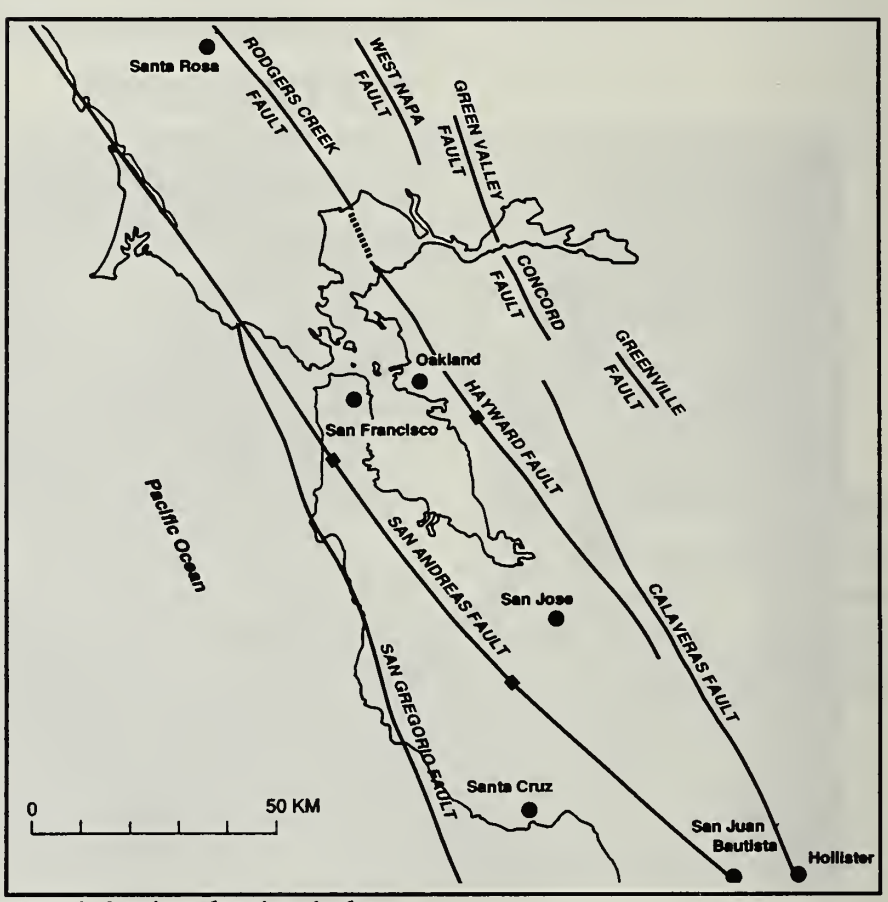
Both its earthquake history and geology show that future damaging earthquakes are inevitable in the San Francisco Bay Area. Although information on active regional faults and damage patterns from past earthquakes provide important clues about where future earthquake damage will occur, the geologic processes that result in earthquakes are not well enough understood for precise prediction of when the earthquake will happen. For this reason, scientists working to understand future earthquakes in the region express their research in terms of probabilities over periods of years.

The Working Group assessed the likelihood of one or more major earthquakes (magnitude 7 or greater and capable of resulting in substantial damage) between 1990 and 2020. Most of our existing structures and infrastructure, as well as most of the new buildings

and public works now contemplated, will probably be in place when the expected earthquake happens.

There is a 67% chance that one or more large earthquake will occur somewhere in the Bay Area by the year 2020.

The Working Group's study uses information from a number of sources, including historical records of earthquakes, on-site studies of faults that provide geological evidence of earlier earthquakes, measurements of the long-term slip rate throughout the entire fault system and on the studied fault segments, and calculations of the energy released in recent earthquakes.



Map 1. Region showing faults.

To carry out the analysis, the major regional faults were divided into segments, portions of the faults that appear to move as a unit during large earthquakes. The segments are shown on Map 1. The San Andreas fault has three segments, the Hayward fault two, and the Rodgers Creek fault one. The probabilities of earthquakes on these fault segments is shown in Table 2.

The entire San Andreas fault system in the Bay Area is estimated to slip about 50 mm (about 2 inches) per year. The individual faults within the system move at different rates, and in different ways. The fault segments included in this study do not account for all of the observed movement in the region's fault system. The movement in excess of what was quantified in the study takes place on other smaller and less understood fault segments. This other movement is not included in these calculations because adequate information is not available. Consequently, the Working Group's probabilities are considered minimum estimates of earthquake potential.

TABLE 2 - EARTHQUAKE PROBABILITIES BY FAULT

Fault Segment	Expected Magnitude	Probability 1990 - 2020
San Andreas Fault		
S. Santa Cruz	8	less than 1%
San Francisco	8	23%
North Coast	8	2%
Hayward Fault		
Southern East Bay	7	23%
Northern East Bay	7	28%
Rodgers Creek	7	22%

Source: Probabilities of Large Earthquakes in the San Francisco Bay Region, USGS Circular 1053, 1990.

The San Andreas Fault

The Working Group estimates the slip rate on the San Andreas fault in the Bay area at about 19 mm (.75 inch) per year. This fault consists of three fault segments in the Bay area, the North Coast segment, which extends from Cape Mendocino to San Mateo County, the San Francisco Peninsula segment which extends from San Mateo County to Santa Cruz County, and the Southern Santa

Cruz Mountains segment which extends to the south. The 1906 San Francisco earthquake involved all of these segments; the Loma Prieta earthquake was located on the Southern Santa Cruz Mountains segment. The Working Group concluded that there is an approximately 23% probability of a large earthquake of magnitude 7 or more on the San Francisco Peninsula segment of the San Andreas fault by 2020. The probabilities are much lower on the segments to the north and south which experienced great displacement in 1906 and 1989.

Hayward Fault

The Working Group estimates the slip rate on the Hayward fault at about 9 mm (.35 inch) per year. This fault consists of two fault segments, the Northern East Bay segment, which extends from San Pablo Bay to the area around San Leandro, and the Southern East Bay segment which extends south to the area around Warm Springs. The last large earthquake on the Northern East Bay segment was in 1836; the last on the Southern East Bay segment was in 1868. The Working Group concluded that there is a probability of approximately 28% and 23% respectively of a magnitude 7 or more earthquake on these fault segments by 2020.

The Rodgers Creek Fault

This fault, which may be an extension of the Hayward fault north into Sonoma County, has been more recently investigated, but is not understood as well as the San Andreas and Hayward faults. The last major earthquake on the Rodgers Creek fault may have been before 1809. The Working Group concluded that there is a probability of approximately 22% of a magnitude 7 or more earthquake on this fault by 2020.

Combined Probabilities

When the probabilities for the various fault segments are combined, scientists conclude that there is a 67% chance that one or more large earthquake will occur somewhere in the Bay Area by the year 2020. This means that a major quake is twice as likely to occur as it is not to occur. Four of these fault segments are located beneath the most heavily populated parts of the Bay Area. As a result, the occurrence of any of these earthquakes could be much more damaging than the Loma Prieta earthquake, even if the magnitude is smaller.

Table 3 - Regional Earthquake Probabilities	
By 1995	*15%*
By 2000	*33%*
By 2010	*50%*
By 2020	*67%*

Source: Probabilities of Large Earthquakes in the San Francisco Bay Region, USGS Circular 1053, 1990

The Working Group has more confidence in its assessment of some fault segments than of others. The assessments of the Southern Santa Cruz Mountain and the North Coast segments of the San Andreas fault are considered the most reliable. The assessments of the Northern East Bay segment of the Hayward fault and the Rodgers Creek fault are considered the least reliable. The Group considers the combined probabilities (those for earthquakes on one or more of the six fault segments) to be significantly more reliable than the probabilities of earthquakes on individual segments.

Observation of historic earthquakes indicates a possible pairing of large earthquakes (magnitude 6.5 or greater) on opposite sides of the Bay, occurring within two to five years of each other. The U.S. Geological Survey, with participation from several universities, has just begun an investigation of the possible relationship between the San Andreas and Hayward faults, trying to determine if they are physically connected in some way at great depth. If a connection is found through these seismic surveys, it may help to explain this pairing phenomenon.

SAN FRANCISCO GEOLOGY AND SEISMICITY

The San Andreas Fault System

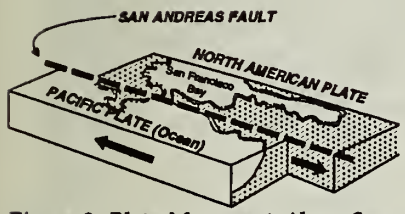


Figure 9. Plate Movement Along San Andreas Fault.
Source: IEEE Spectrum, Sep 1973

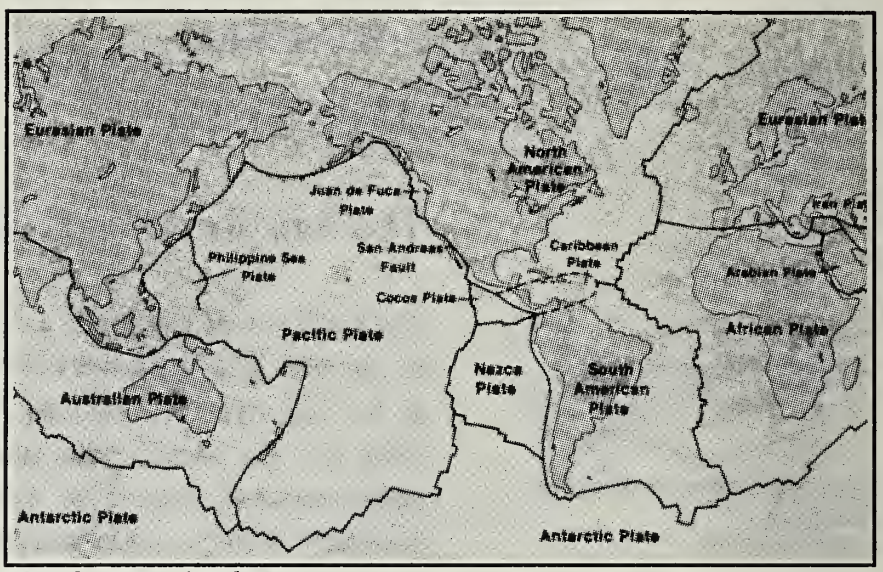
The earth's crust comprises a dozen or so "tectonic plates": pieces of the crust that move very slowly over the surface of the earth. In the Bay Area, two of these plates meet near the coast. (See Map 2.) The Pacific Plate, under the Pacific Ocean, is moving northwestward relative to the North American Plate. Their boundary is the San Andreas fault system.

The San Andreas fault system is a complex network of faults that extends throughout the Bay area. (See Map 1.) It consists of a zone of crushed rock extending over 800 miles long, about 10 miles deep, and from a few hundred feet to a few tens of miles wide. It includes the San Andreas, Hayward, Rodgers Creek, Calaveras, and many smaller faults.

Figure 10. San Andreas Fault at Crystal Springs Reservoir.
Photo: R.E. Wallace, U.S. Geological Survey

The Pacific plate and the North American plate have moved about 350 miles relative to each other over the last 15 to 20 million years. Recent surveys show that this movement continues at a rate of about 50 mm (about 2 inches) per year, which is consistent with the long-term estimates. This movement occurs in different ways, unevenly over the lengths of the different faults which make up the fault system. Some segments of faults creep almost constantly, slowly damaging any structures built astride them. Other sections

of the fault remain quiet over many years while strain builds up, to be released suddenly in great earthquakes. During the 1906 earthquake, the San Andreas fault slipped as much as 18 feet along a 225-mile segment from San Juan Bautista to Cape Mendocino. During the 1989 Loma Prieta earthquake, a 25-mile segment of the San Andreas fault slipped about seven feet.



Map 2. Tectonic Plates

The faults which make up the San Andreas fault system can often be easily recognized from the air as a linear strip of lakes, bays and valleys. In the Bay area, the San Andreas fault runs through the Crystal Springs Reservoir, under the Pacific Ocean about one mile west of the southwest corner of San Francisco, and through Tomales Bay. The Hayward fault, which is also part of the San Andreas fault system, runs along the western base of the hills in the East Bay, from San Pablo Bay to San Jose. It is about 10 miles northeast of San Francisco at its closest point. While no known active faults exist in San Francisco, major earthquakes occurring on the faults surrounding the City have resulted in substantial damage within the City. Similar damaging earthquakes in the future are inevitable.

TABLE 4- Richter Scale	
Magnitude	*Effects*
8	*Great Earthquake*
7	*Major Destructive Earthquake*
6	*Moderately Destructive Earthquake*
5	*Causes Light Damage,mostly nonstructural*
4	*Felt a few miles from epicenter*
3	*Barely felt, no damage reported*
2	*Can be barely felt near epicenter*
1	*Observed only by instruments*

Measures of Earthquake Severity

Magnitude

The size of an earthquake is usually expressed in terms of its Richter magnitude which describes the energy released at the earthquake source. For any given site, an increase of 1 in magnitude implies ten times the ground shaking; a magnitude 7 earthquake has ten times as much ground motion as a magnitude 6 earthquake. Each earthquake has one magnitude. (This is a different concept from measurements of ground shaking intensity, which will differ for each location. See the discussion of ground shaking, below, for a description of measurements of intensity.)

Acceleration

As the earthquake waves start propagating through the ground, the ground moves back and forth. Acceleration is the measurement of the *rate of change* of this motion, and is usually expressed as a percent of gravity. This is a useful measurement for engineers who then translate expected accelerations into the forces to which a building will be subject during an earthquake. The level of acceleration generally considered sufficient to produce some damage to weak construction is 0.1g (10% of the force of gravity). At between 0.1g and 0.2g most people will have difficulty keeping their footing and may begin to feel ill. In the Loma Prieta earthquake, peak horizontal ground accelerations of between 0.17 (at the Civic Center) and 0.24g (at Fort Point) were recorded in San Francisco. Peak accelerations of 0.64g were recorded near the epicenter.

Duration

In the 1906 San Francisco earthquake, severe shaking lasted about 45 seconds. In contrast, strong ground shaking in the Loma Prieta earthquake lasted about 10 seconds, an unusually short period of time for an earthquake of that magnitude.

The duration of strong ground shaking is another important measure of earthquake severity. Larger earthquakes usually have a longer duration of strong ground shaking. For example, in the 1906 San Francisco earthquake, severe shaking lasted about 45 seconds, and in the 1868 San Francisco/Hayward earthquake strong ground shaking lasted about 42 seconds. In Mexico City in 1985 the strong ground shaking lasted over a minute and in the 1964 Alaska earthquake it lasted at least two minutes. In contrast, strong ground shaking in the Loma Prieta earthquake lasted about 10 seconds, an unusually short period of time for an earthquake of that magnitude. Obviously, the longer the ground shakes, the greater the damage to most structures.

Structures may continue to move even after the ground has stopped shaking, depending on soils, location of the earthquake, and flexibility of the building. Even within one building, different floors may experience different acceleration levels and different durations of shaking. For example, the top floors in a flexible tall building may sway longer than the lower floors.

San Francisco Soils

The location and movement of earthquake faults is only one of the factors which results in earthquake risk. Even in locations which are relatively far from faults, soils can intensify ground shaking, or the ground may settle or slide. For example, during the Mexico City magnitude 8.1 earthquake of 1985, the most devastating damage was over 200 miles from the fault in an area of weak soils. The parts of San Francisco which experienced the greatest damage in 1989 were not those closest to Loma Prieta, but those with soils which magnified ground shaking, liquefied, or slid. These were many of the same areas which experienced damage in 1906.

The hills along the central spine of the San Francisco peninsula are composed of rock and soils which are less likely to magnify ground shaking, although they are sometimes vulnerable to landsliding during an earthquake. Bedrock in the most vulnerable parts of San Francisco is covered by soils which have been deposited naturally over hundreds of thousands of years as well as by artificial fill deposited by humans over the last 150 years or so. The soils most likely to result in hazards during an earthquake are in low-lying and filled land along the Bay, in low-lying valleys and old creek beds, and to some extent, along the ocean.

Bay Mud

The soils most likely to result in hazards during an earthquake are in low-lying and filled land along the Bay, in low-lying valleys and old creek beds, and to some extent, along the ocean.

During the last million years the ocean level has risen and receded at least four times as a result of the formation and melting of glaciers. During the periods of low water, valleys eroded. During times of higher ocean levels, mud and sand were deposited on what is now San Francisco. Areas adjacent to the Bay are underlain by soft Bay mud: a geologically young mixture of sands, clay and gravel deposited during the past 10,000 years following the last period of glaciation. Because Bay mud was deposited relatively recently, it has not been compacted and remains loose. Because of its heterogenous nature, it is not stable, and is more likely to behave erratically when shaken. During earthquakes, water saturated Bay mud can liquefy and tends to shake considerably more than the underlying bedrock. (See discussions of ground shaking and liquefaction below.)

In the Marina District the Bay mud is nearly 100 feet thick. During the 1906 earthquake, even before the area had been filled, the Marina District experienced some of the most severe ground shaking in San Francisco because of this layer of Bay mud.

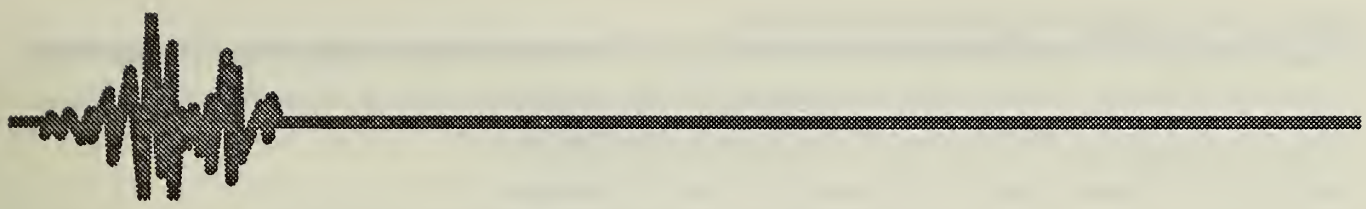
Artificial Fill

The problems of increased ground shaking on Bay mud are compounded by the artificial fill which was used to extend the

buildable land into marshes, lagoons and open water over the last 150 years. Much of the artificial fill which was placed on the margins of the Bay in San Francisco, over naturally occurring soft Bay mud, consists of mixed sand and miscellaneous debris. It was placed before soils engineering and ground preparation techniques to stabilize fill were developed. This older "unengineered" fill has not been mechanically compacted and may contain organic material. As a result this "made ground" shakes more intensely than the underlying bedrock during earthquakes, and, when it is water saturated, is susceptible to ground failure, particularly liquefaction. (See discussions of ground shaking and ground failure below.) The qualitative differences between unengineered and engineered fill partially account for the higher levels of damage in areas like the Marina and the South of Market than in new filled areas such as Foster City.

Dune Sand

Much of the City downhill from the central spine of hills and uphill from the Bayside and creekbed Bay mud deposits consists of fairly flat dune sands. This fine-grained, well-sorted (with grains of similar size) sandy soil was deposited by wind action between 10,000 and 100,000 years ago. Its stability depends on its age and the degree of water saturation. This sand shakes during earthquakes more than the underlying bedrock. If water saturated, it can liquefy. The water table in most of these parts of San Francisco except for the area closest to the ocean and Lake Merced is not so high that liquefaction is considered likely, as shown on Map 7. (See discussions of ground shaking and liquefaction below.)



GEOLOGIC HAZARDS

The movement of faults during earthquakes results in a variety of natural phenomena which have the potential to damage buildings and other structures and to disrupt and even endanger our daily lives. Different combinations of these earthquake effects can occur in different earthquakes and at varying distances from the earthquake source. An understanding of these natural hazards and how they result in damage can lead to more effective safety planning at a City-wide policy level, and to better decisions about the uses of individual lots. URS/John A. Blume & Associates produced a study for the 1974 Safety Element which describes these hazards City-wide. Although subsequent reports have resulted in some more detailed and refined information, the *San Francisco Seismic Safety Investigation* remains a valid overview of geologic risks. The following discussion summarizes that report, and other more recent studies describing the primary earthquake hazards most likely to result in damage in San Francisco:

- **Ground shaking** is the most geographically wide-spread effect of earthquakes, occurring throughout the region.

- **Surface rupture** occurs directly along the fault.

- **Ground failure** occurs when soil which is saturated with water, is on a slope, or is otherwise weak, cannot support structures, or even itself, after being subjected to ground shaking.

- **Other hazards** which can result from earthquakes include tsunami and seiches.

In 1990, the California Legislature enacted the Seismic Hazard Mapping Act (Chapter 7.8, Public Resources Code sections 2690 et seq.). Pursuant to this act, the Division of Mines and Geology is preparing maps of strong ground shaking, liquefaction, landslides and other ground failure. The maps for San Francisco are expected to be completed in 1993.

Ground shaking

Most earthquake damage comes from ground shaking. Ground shaking occurs in all earthquakes. All of the Bay area and much of California are subject to some level of ground shaking hazard. In a major earthquake it extends over a very large geographic area. The impacts of ground shaking will be quite widespread, and are much less predictable than those of surface rupture. As happened in the Loma Prieta earthquake, some areas will be hard hit while others are relatively unaffected.

During an earthquake, many different ground shaking intensities will occur, but each earthquake has only one magnitude.

The severity of ground shaking varies considerably over the impacted region depending on:

- the size of the earthquake
- the distance from the fault segment that generated the earthquake
- the nature of the soil at the site
- the nature of the geologic material between the site and the fault

Because ground shaking varies by location during any earthquake, it is measured in intensity (as opposed to the earthquake's magnitude). Intensity measures the *effects* of ground shaking during an earthquake, while magnitude measures the earthquake's *size*. During an earthquake, many different ground shaking

intensities will occur, but each earthquake has only one magnitude. Intensities are measures of the effect of the earthquake at a given location, and are a more subjective measurement. The Modified Mercalli scale is the most common way of describing ground shaking intensity. The San Francisco intensity scale has been used in several studies of the San Francisco area, including the Blume report of 1974 and ABAG's 1987 study. The Modified Mercalli Scale ranges from a low of MM I to a high of MM XII. The San Francisco Scale ranges from a low of <E to a high of A. Both scales measure the effects of ground shaking, although the San Francisco Scale is more focused the effects on structures. There is not a one-to-one correspondence between the two scales. These two scales are summarized and compared in Table 5.

During the Loma Prieta earthquake, Modified Mercalli Intensity IX (MM IX) was felt in the Marina District, portions of the South of Market, and the Cypress structure area in Oakland. The western and central part of San Francisco experienced MM VI. The area around the epicenter experienced MM VIII.

A 1987 Association of Bay Area Governments (ABAG) study explored ground shaking in future earthquakes. The study, *On Shaky Ground*, includes a series of maps showing the ground shaking intensities likely to be experienced in the Bay area, and the patterns of structural damage likely to result. This project depended on several different sets of information:

- Assumptions about the size and duration of expected earthquakes, based on the locations of faults and the magnitudes and probabilities of earthquakes on those faults.
- Geologic materials, which were mapped and grouped together into categories of similar susceptibility to shaking from earthquakes.

TABLE 5 - GROUNDSHAKING INTENSITY SCALES

Modified Mercalli Scale (summarized)

XII - Panic is general; damage is total; practically all works of construction damaged greatly or destroyed.

XI - Panic is general; damage is severe to wood frame structures; few if any masonry structures standing.

X - Panic is general; well-built wood frame structures are severely damaged, some collapse; few if any masonry structures standing.

IX - Panic is general; Damage is considerable in masonry structures built especially to withstand earthquakes, great in other masonry buildings, some collapse; some wood frame houses built especially to withstand earthquakes are thrown out of plumb.

VIII - General fright and alarm; Damage is light in masonry structures built especially to withstand earthquakes, considerable in ordinary substantial buildings, some collapse; heavy damage in some wood frame houses; very heavy furniture moves conspicuously or overturns.

VII - Frightens everyone, everyone runs outdoors; Damage is negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or designed buildings; plaster and some stucco fall; weak chimneys and cornices fall.

VI - Felt by everyone, awakens all sleepers, general excitement; Poorly built buildings may be damaged; plaster falls and cracks; knick-knacks, books, pictures fall.

V - Felt indoors by almost everyone, awakens many sleepers, slight excitement; buildings tremble; some windows crack; hanging objects swing considerably.

IV - Felt indoors by many, awakens light sleepers; vibration like that due to passing of heavy trucks; dishes, windows and doors rattle.

III - Felt indoors by some; vibration like that due to passing of a light truck some distance away.

II - Felt indoors by a few, especially on upper floors of tall buildings, and by sensitive or nervous people.

I - Not felt by people except under especially favorable circumstances.

San Francisco Scale

A - Very Violent. Rending and shearing of rock masses and all structures along the line of faulting; some structures totally destroyed.

B - Violent. Fairly general collapse of brick and frame buildings when not unusually strong; serious cracking of brick work and masonry in excellent structures; broad wave-like folds in paved and asphalt-coated streets; destruction of foundation walls; the breaking of sewers and water mains.

C - Very Strong. Brick work and masonry badly cracked, with occasional collapse, frame buildings with fair or weak foundations lurch or list; general destruction of chimneys and of masonry, brick or cement veneers.

D - Strong. General but not universal fall of chimneys; cracks in masonry and brick work; cracks in foundations walls, retaining walls, and curbs; a few cases of lurching or listing frame buildings with weak underpinning structures.

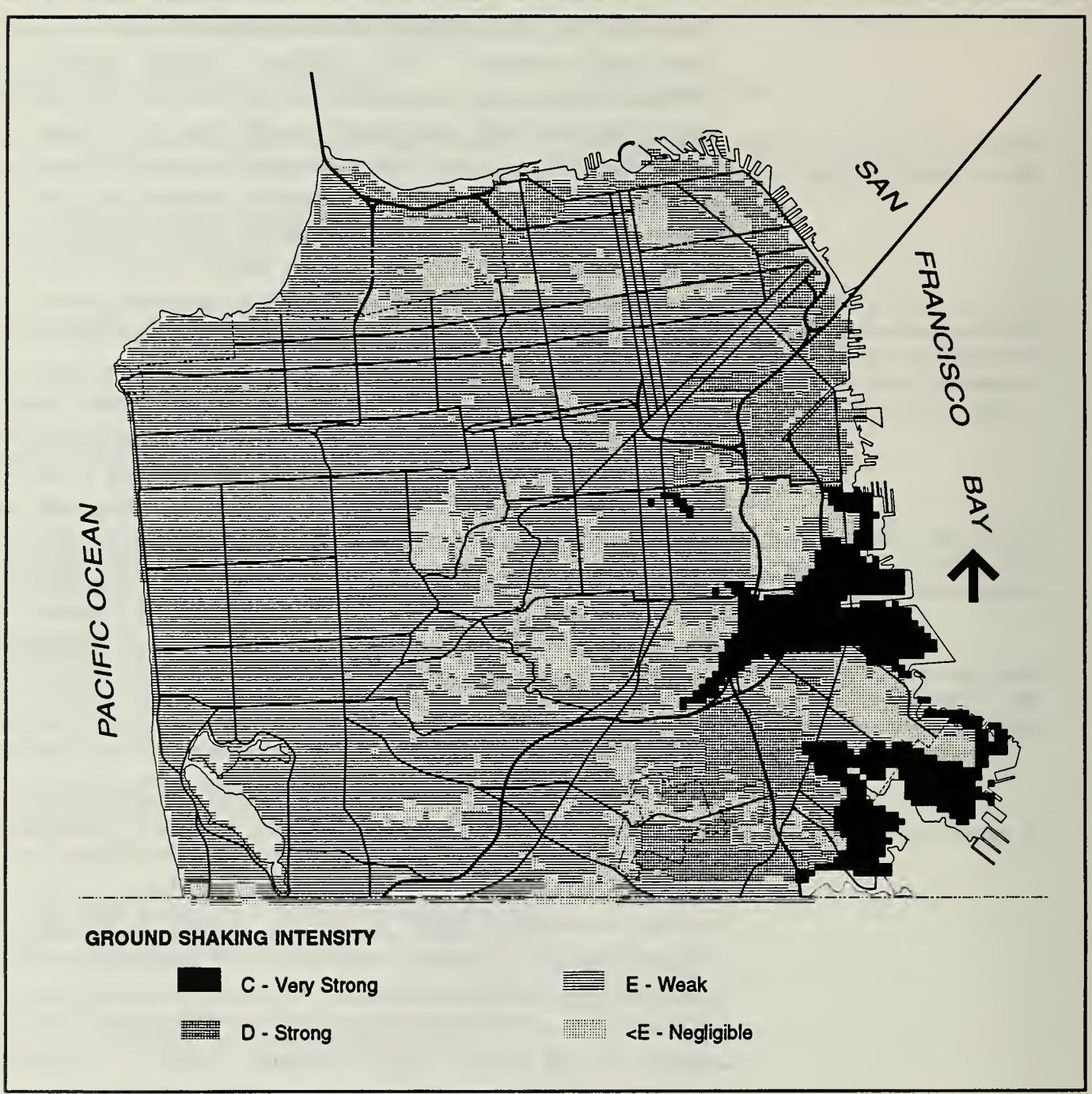
E - Weak. Occasional fall of chimneys and damage to plaster, partitions, plumbing.

<E - Negligible

Ground shaking effects of possible large earthquakes on 31 active faults were evaluated. They included relatively probable earthquakes (with likely recurrence intervals of 70 or 100 years) and earthquakes which occur less frequently, but will be quite severe when they do occur. Intensity maps for two of the most probable earthquakes, magnitude 7 on the San Andreas fault, and magnitude 7 on the Hayward fault are shown on Map 3 and Map 4. A comparison of these maps shows that the intensities of ground shaking will vary considerably throughout the City during any given earthquake, and that the pattern of groundshaking is fairly consistent, reflecting the underlying soils. In general, sites with stronger soils (those in the hills and higher land) will experience less intensity than those in low-lying areas and along the Bay, with Bay mud or other weaker soils. During a San Andreas fault earthquake the intensity would be marginally greater in the southwest portion of San Francisco than during a Hayward fault event (although still not as great as in the areas with the weakest soil), while during a Hayward fault earthquake effects in the northeastern part of San Francisco would be more severe than during the San Andreas event.

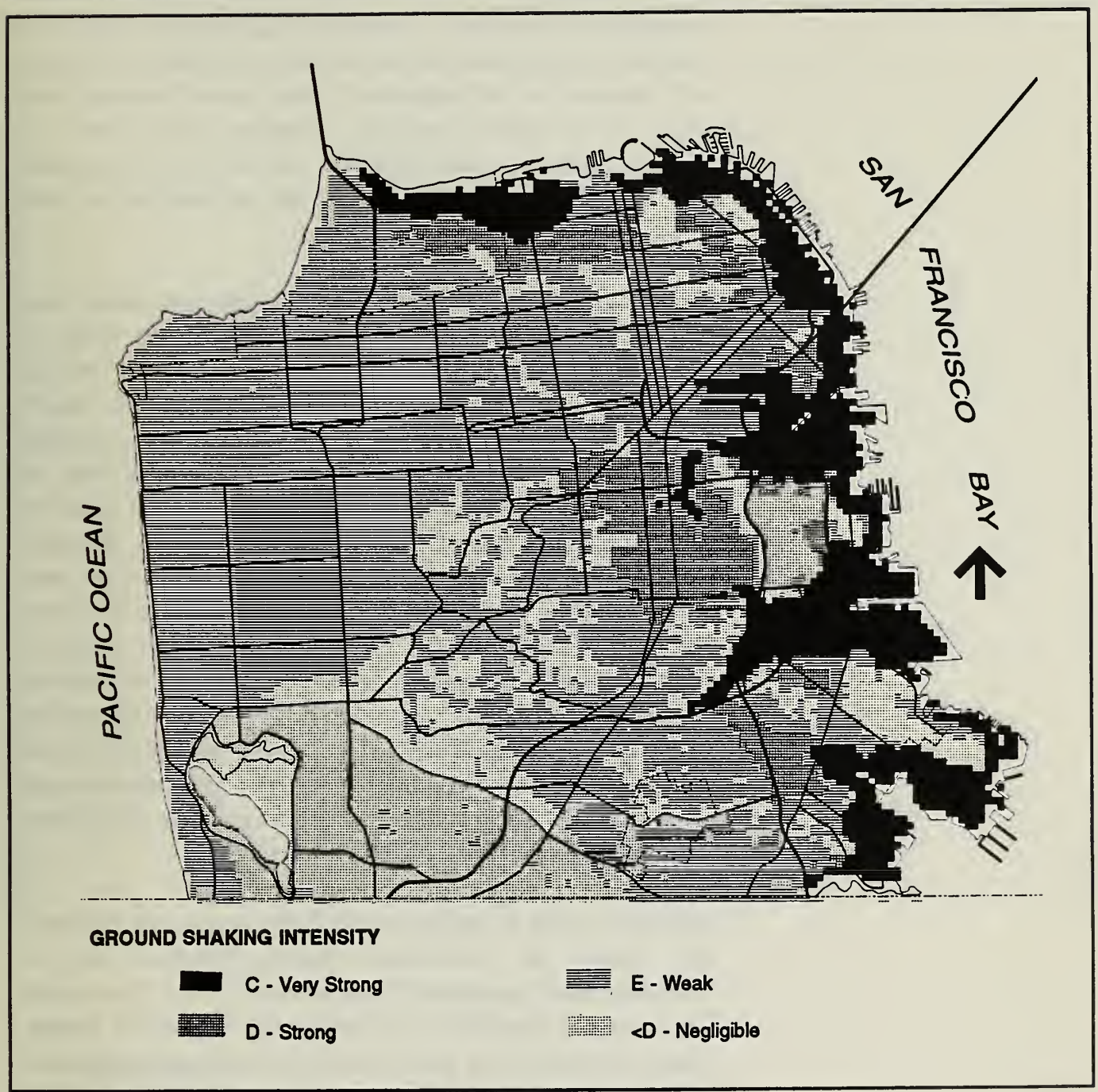
ABAG consolidated this information in two different ways. First, the "Maximum Ground Shaking Intensity" map shows (on one map) the highest intensity which would occur at any site during any of the 31 analyzed earthquakes. It shows that the softer soils on the low-lying land in the eastern parts of the City, and the extreme southwestern corner of the City (closest to the San Andreas fault) could experience intensity level "B" (violent) ground shaking during a possible earthquake. The hills in the central part of the City could experience intensity level "E" (weak) to "D" (strong) ground shaking, while the bulk of the City could experience intensity level "C" (very strong) ground shaking.

The Maximum Ground Shaking Intensity map treats the 31 earthquakes equally. Some of these possible earthquakes are much more likely to occur than others (see the discussion of earthquake



Map 3. Ground shaking from Magnitude 7 San Andreas Fault Earthquake.

Source: Association of Bay Area Governments



Map 4. Ground Shaking from Magnitude 7 Hayward Fault Earthquake

Source: Association of Bay Area Governments

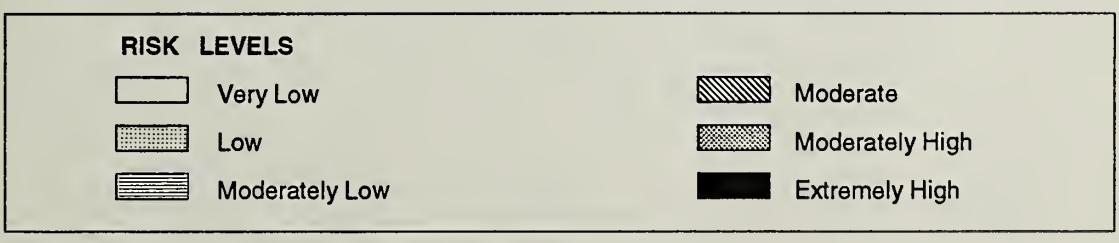
probabilities). Some sites, particularly those with poor soils, will experience strong ground shaking in most earthquakes. Some sites with stronger soil will experience strong ground shaking only when a nearby fault is involved. Particularly when choices are required, property owners and policy makers need to know how likely these levels of ground shaking are, and what the impacts would be.

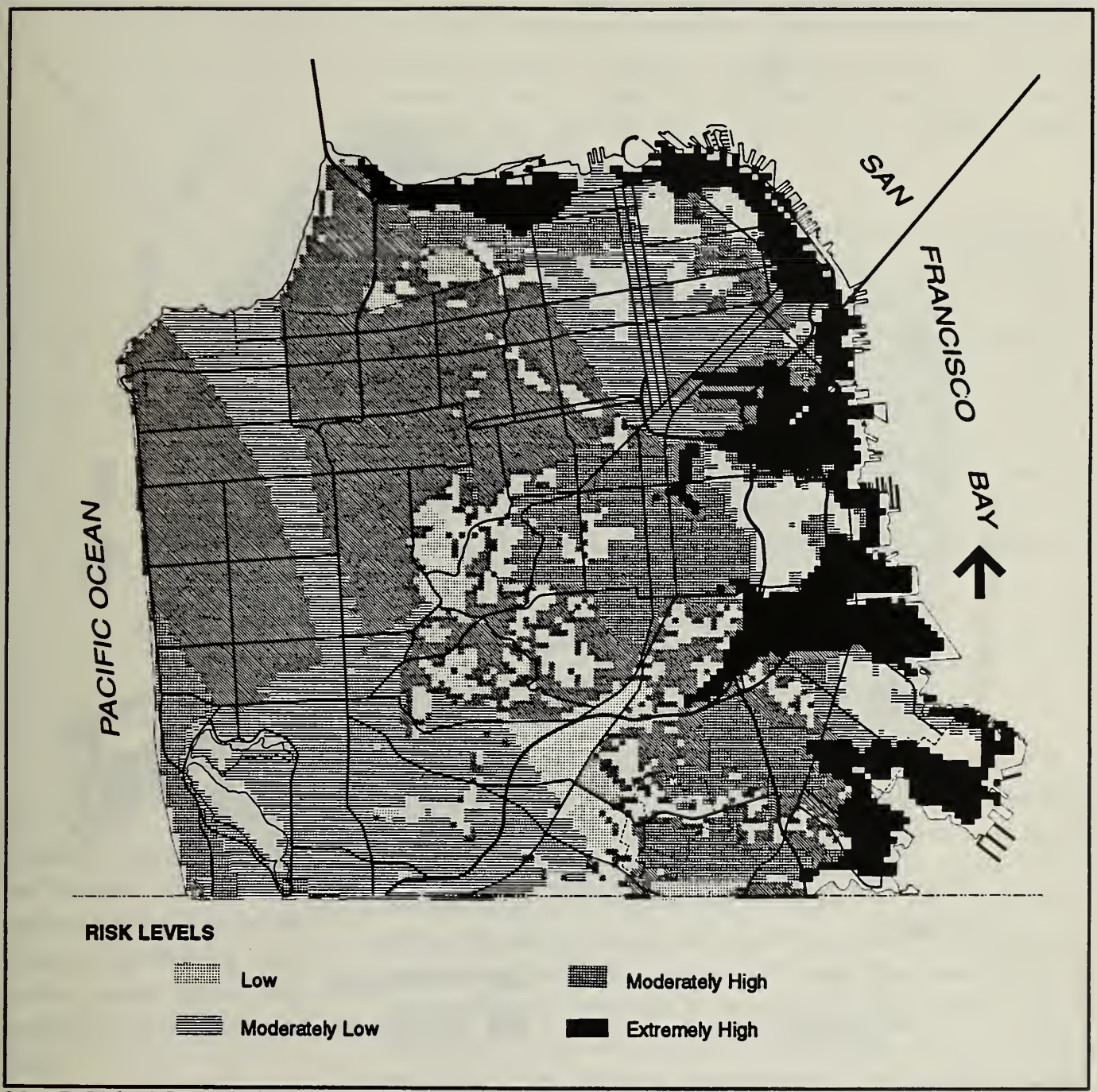
The second way that the ABAG study uses this information is to describe the effect of ground shaking on different kinds of buildings. In order to map "Cumulative Damage Potential", ABAG used data on expected damage to selected building types. Map 5 shows the risk of ground shaking damage for well-built unreinforced masonry buildings (the building type most likely to suffer damage from ground shaking). Map 6 shows the risk for wood frame dwellings (the building type least likely to suffer damage). Other building types would fall between these two. These data about ground shaking are weighted according to how likely the different earthquakes and resulting intensity levels are to occur. Risk is expressed in terms of the percent of expected damage (the cost of repairing a building divided by the cost of replacing the building), multiplied by the recurrence interval of the earthquake, and discounted to present value. This analysis is not based on inventories of buildings, so it does not show the number of buildings at risk.

Map 5 shows that in the parts of the City underlain by Bay mud and artificial fill, unreinforced masonry buildings face an "Extremely High Cumulative Damage Potential" of 6.1% or more. (This does not mean that in an earthquake they would sustain damage equal to 6.1% or more of the cost to replace. It means that the likely damage from earthquakes, over time, and discounted to present value is over 6.1%.) In other parts of the City the risk is lower. Reinforced concrete buildings and steel frame buildings are expected to perform better; in areas with the highest ground shaking potential, they have "High" cumulative damage potential

ERRATUM:

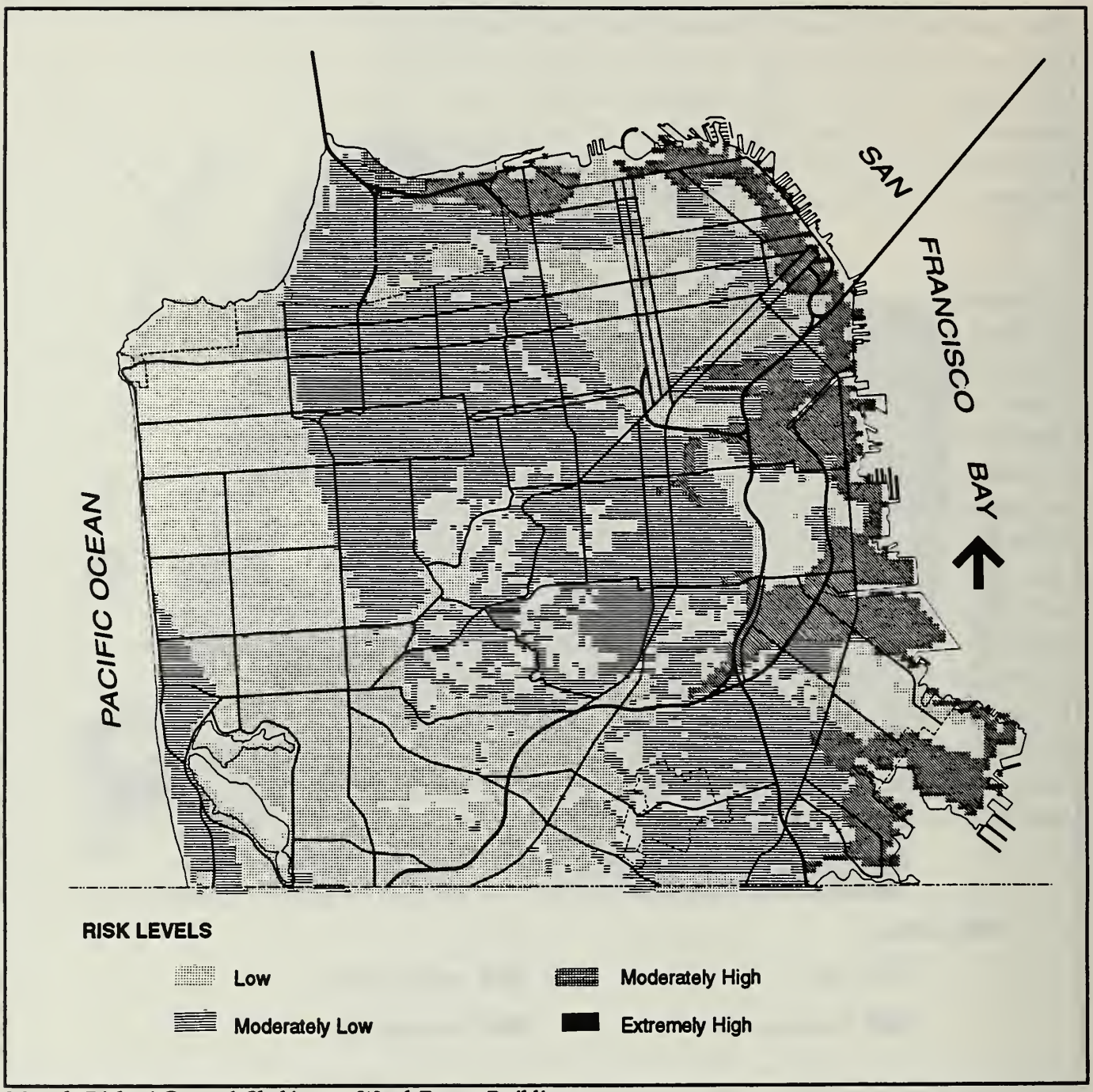
The legend for Map 5 (page 27) and Map 6 (page 28) should read as follows:





Map 5. Risk of Ground Shaking to Unreinforced Masonry Buildings

Source: Association of Bay Area Governments



Map 6. Risk of Ground Shaking to Wood Frame Buildings

Source: Association of Bay Area Governments

(4.1 - 5%). Wood Frame buildings in these most vulnerable areas have a "Moderate" cumulative damgae potetial (2.1 - 3%), as shown on Map 6. These maps illustrate that *both* soil type and building type influence the risk of damage to buildings from ground shaking.

Immediately after the 1989 Loma Prieta earthquake, instruments at five sites in and near the Marina district measured ground shaking during aftershocks. They found that earthquake motions in the Marina district were significantly stronger than motion on nearby bedrock at Fort Mason, Pacific Heights, and Nob Hill. The aftershocks ranged from magnitudes of 2.1 to 5.0; they were amplified by the underlying Bay mud throughout much of the district by factors ranging from 2 to 10. Other earthquakes would have different ranges of amplification, depending on a number of factors including the size of the earthquake and its distance from the site.

Surface Rupture

The utility and transportation systems serving San Francisco are part of a regional system that will be seriously affected by fault rupture outside of the city, particularly on the Hayward fault.

The most obvious and direct earthquake effect is the rupture of the ground surface along the fault. Ground rupture occurs in some, but not all, large earthquakes. For example, there was no ground rupture during the Loma Prieta earthquake, but during the 1906 earthquake, surface rupture was noted for 225 miles along the fault, from San Juan Bautista to Cape Mendocino. At its maximum point, near Point Reyes, there was 20 feet of offset, meaning that fences and roads were offset by as much as 20 feet. Structures are unable to withstand surface rupture such as that. Streets, utilities and other lifelines which cross an earthquake fault are at great risk of damage.

Active faults in California are mapped by the California Division of Mines and Geology, as part of the Alquist-Priolo Special Studies Zones program, which regulates building near active faults. (The Alquist-Priolo program was created by the legislature in 1972. It

will be discussed in more detail in Background Report 2, Current Policies and Programs.) The impacts of this effect, while locally severe, are not widespread and are relatively predictable. It is very difficult to design a structure to withstand the effects of surface rupture. Consequently, the Alquist-Priolo program generally prohibits substantial building on an active fault.

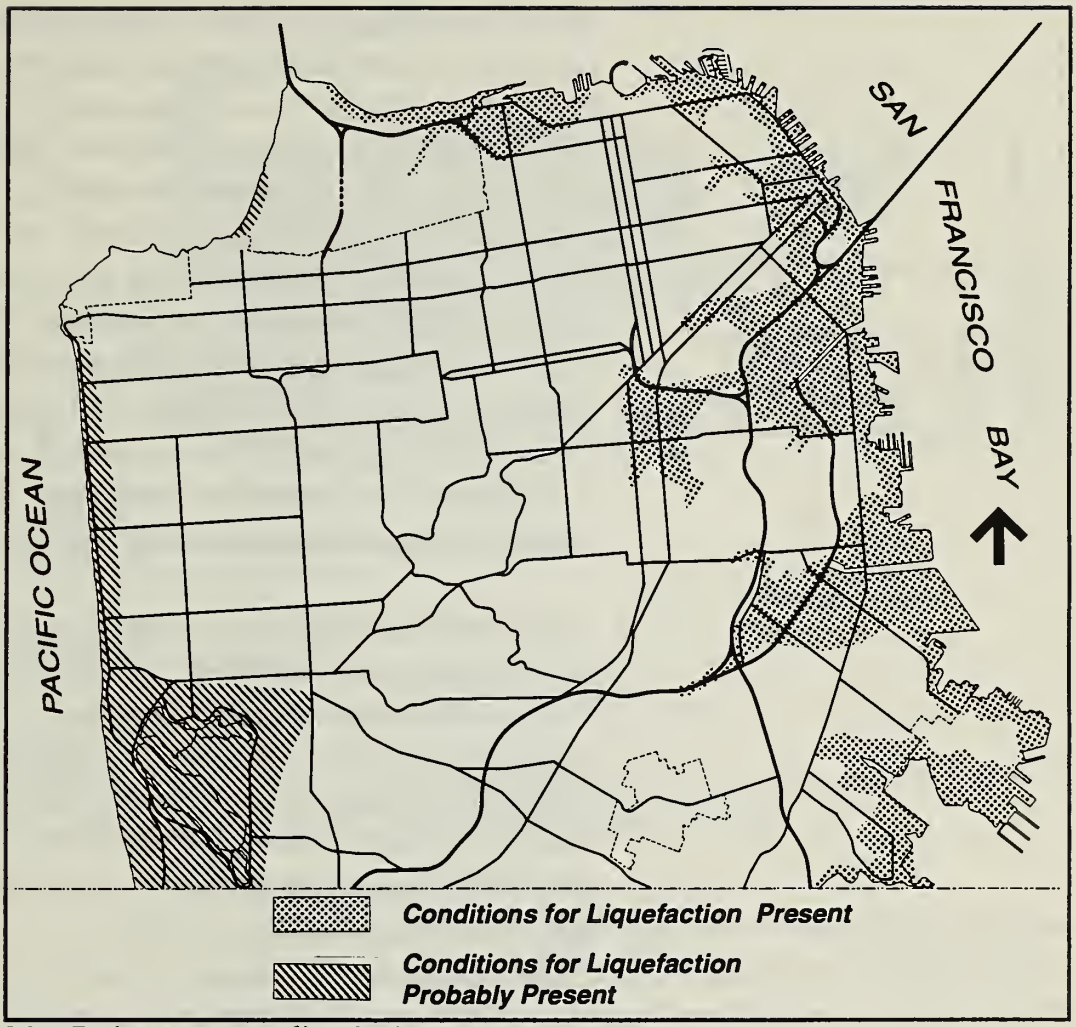
There are no active faults within the boundaries of San Francisco. However, the lack of active faults does not mean that San Francisco will be unaffected by this hazard. The utility and transportation systems serving San Francisco are part of a regional system that will be seriously affected by fault rupture outside of the city, particularly on the Hayward fault.

Ground Failure

"Ground failure" means that the soil is weakened so that it no longer supports its own weight or the weight of structures. Ground failure can happen in the absence of earthquakes. For example, landsliding is often a continuing natural process by which land uplifted by geological processes erodes over time. Ground failure can be aggravated by human actions. It can also occur suddenly and catastrophically during earthquakes. The major types of ground failure associated with earthquakes are liquefaction, landslides, and settlement.

Liquefaction

Liquefaction is the transformation of a confined layer of sandy water-saturated material into a state possessing properties of a liquid as a result of earthquake shaking. When soil liquefies during an earthquake, water may spout out of the ground, sandboils (sand and water seething from holes in the ground) appear. Buried tanks can float to the surface. More seriously, a



Map 7. Areas prone to liquefaction.
Source: URS/John A. Blume and Associates

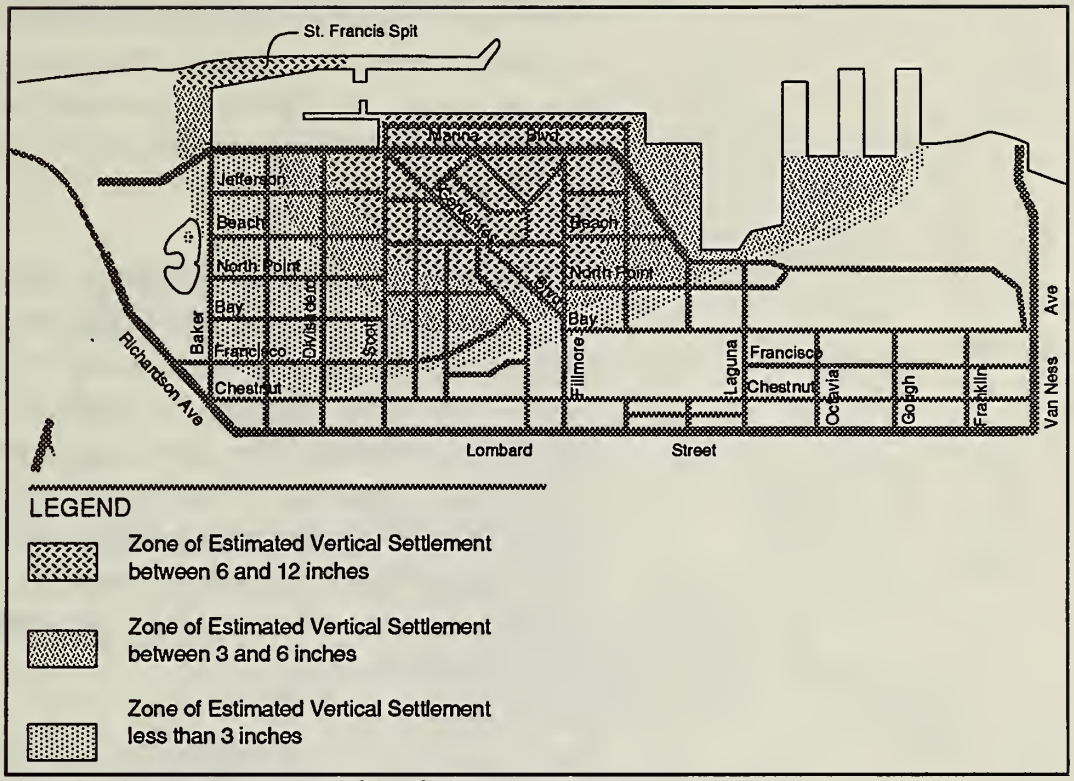
structure or parts of structures no longer supported by the soil can tilt, sink or break apart. Underground utilities can be substantially damaged.

Liquefiable soils include sandy soils with very low clay content at or below the water table. Locally, such areas involve uncompressed artificial fill, unconsolidated sand, or dune sand, with a high water level. The Blume report shows these areas at a general level of detail. (See Map 7). These areas are generally filled areas along the Bay front and former Bay inlets, and sandy low-lying areas along the ocean front and around Lake Merced.

Recent investigations provide more specific information about liquefaction potential in some of these vulnerable areas. The Department of Public Works commissioned a study of liquefaction and its impacts on the Municipal Water Supply System (MWSS), the Auxiliary Water Supply System (AWSS), and the sewer system in some susceptible areas: the Marina district, Sullivan Marsh (South of Market), Mission Creek area, South Beach area, the Embarcadero waterfront, and the Telegraph Hill/North Beach area. This study includes the collection and evaluation of geotechnical data, the inventory of the underground utilities, an evaluation of damage to underground utilities caused by ground movements in a magnitude 8.3 earthquake, evaluation of feasible mitigation measures and recommendations for mitigation measures.

The Marina district and Sullivan Marsh portions of the study have been completed and published. After reviewing soil conditions, the Marina district was divided into areas with similar potential for ground settlement as a result of liquefaction. (See Map 8.) During a magnitude 8.3 earthquake, a semi-circular area with its base on the Marina Green and extending south of Beach Street, and the St. Francis Spit (a spit of land at the north of the yacht basin which contains the St. Francis Yacht Club and the Wave Organ), could settle as much as twelve inches. Because of the presence of a large, relatively geotechnically-stable box sewer under Marina Boulevard, the Marina Green will settle more than the blocks south of the Boulevard. The rest of the district, extending to Baker Street on the west, almost to Chestnut Street on the south, and curving back to Fort Mason, would probably settle an average of less than six inches. These estimated settlements are about 1.5 to 2 times higher than those observed in 1989.

The report estimates that the magnitude of lateral (sideways) ground displacement will be similar to that of vertical displacement, with the exception of the St. Francis spit where lateral displacement could be five feet or more. The lateral displacement caused by the 1989 earthquake on the St. Francis spit was about two feet.



Map 8. Liquefaction potential in the Marina District.
Source: Harding Lawson & Associates, Dames & Moore, Kennedy/Jenks/Chilton, EQE

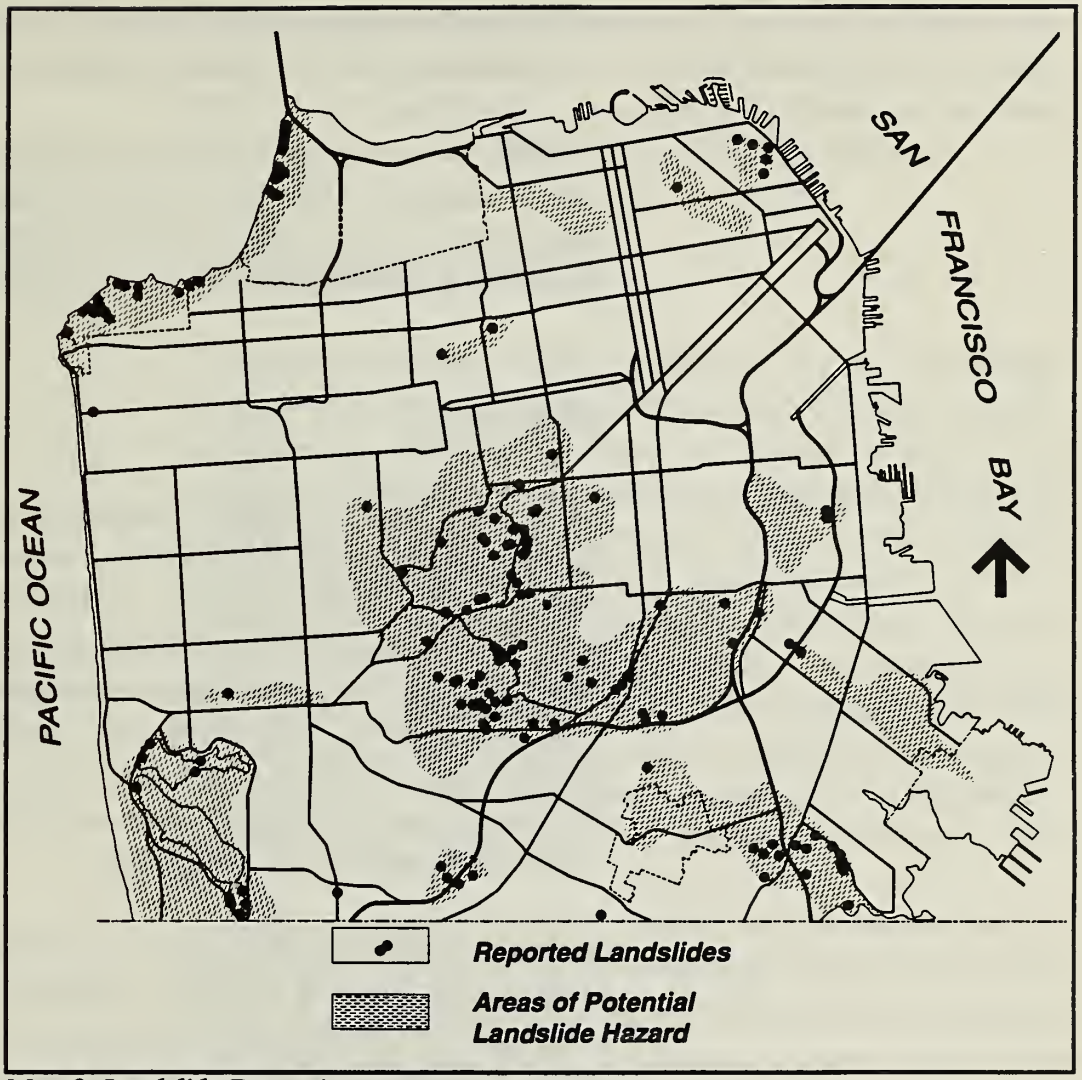
The Sullivan Marsh area extends east to west diagonally across the square formed by Market, Third, Townsend and Eighth Streets. Significant ground failure occurred here during the 1906 and 1989 earthquakes. Settlement due to liquefaction is expected to vary substantially, ranging up to five feet on parts of the blocks generally between Mission, Fifth, Folsom and Seventh Streets. Lateral displacement is expected to vary, with a high of two feet in that same area. In a large earthquake, this liquefaction-induced ground movement would result in substantial damage to the water and sewer systems in the Marina and Sullivan Marsh areas.

Area-specific geologic studies of the Mission Bay area were undertaken in 1986. They assessed soils conditions and the implications of these conditions for future development. The Mission Bay area is a 300-acre site, most of which was a large shallow bay which has been filled since 1865 and is underlain with

sedimentary deposits, including 30 to 100 feet of Bay mud. These conditions are similar to much of the northeastern and eastern shoreline area of San Francisco. In a major earthquake, these soil conditions can produce increased ground shaking, liquefaction, and settlement.

Also considered were risks to buildings, risks to lifeline systems, and preparedness planning. The study concluded that properly-designed pile foundations can provide protection for buildings against liquefaction expected in Mission Bay, and that the development of appropriate seismic design criteria, good structural design and supervision of the design process (in addition to compliance with the applicable building codes) will lower the risk of injury from building failure in Mission Bay compared to the risk potential in some other areas of San Francisco where older buildings predominate.

The consultants concluded that the performance of underground utilities can be improved through better technology in Mission Bay. Nevertheless, damage to streets and to underground utilities will still be much greater than in parts of the City with better soil conditions. Consequently, emergency generators should be provided at important facilities, and the underground systems should be supported with redundant design. However, the consultants did not feel that large-scale soil stabilization efforts would be cost-effective, except perhaps at locations with city-wide or regional importance, such as the bridge approaches. Because the elevated freeways and the streets beneath them and the Third Street and Fourth Street drawbridges may be impassable after an earthquake, alternative ways into and out of Mission Bay should be provided.



Map 9. Landslide Prone Areas.
Source: URS/John A. Blume and Associates

Landslides

A landslide is a movement of a mass of soil down a slope when the soil loses strength to the extent that it can no longer support the weight of overlying soil or rocks. Landslides vary in size and rate of movement. They occur naturally in susceptible areas. Although earthquakes are rarely the sole cause of landslides, land that is weakly supported because of natural erosion, changes in

ground water or surface water patterns, or human activities such as undercutting, often slides during large earthquakes.

A major earthquake in San Francisco may cause movement of active slides and could trigger new slides similar to those which have already occurred under normal conditions. General areas vulnerable to landslides were identified in the Blume report. (Map 9).

Settlement

Settlement (sometimes called subsidence by geologists) is process by which poorly compacted naturally or artificially deposited soils become more compact over time. It is more likely to occur in sandy than in clayey soils, in younger than in older soils, and in soils containing a mixture of materials or grain sizes resulting in more void spaces. Soil settles and compacts naturally over geologic time as a result of gravity and the weight of soil and structures above it. Earthquakes can set off rapid and sometimes uneven local settlement of the ground.

Settlement under a structure can cause substantial damage. It is most likely to occur in filled areas along the waterfront, where non-engineered artificial fill was deposited over weak young Bay muds. Substantial settlement occurred during the 1906 and 1989 earthquakes. When settlement is uneven, it is especially hazardous to the structures above. Large buildings and facilities such as roads or pipelines, which extend over different types of soil, are the most vulnerable. Such differential settlement resulting from improved ground can produce unintentional damage. Improved ground associated with underground engineered works in the Marina settled less than unimproved ground. For example, a home over a storm drain outfall tilted because the portion of the building not on the outfall settled more than the portion on the outfall.

The Blume report shows that the areas of potential subsidence are similar to, and smaller than, the areas of potential liquefaction on the east and north side of the City. It shows no potential subsidence areas along the ocean or near Lake Merced.

Tsunami and Seiches

Tsunami (sometimes incorrectly called tidal waves, even though they have no connection with tides) are large waves in the ocean generated by earthquakes, coastal or submarine landslides, or volcanoes. Damaging tsunami are most common in Pacific islands, such as the Hawaiian Islands and Japan, and in Alaska. They are not common on the California coast. Most California tsunami are associated with distant earthquakes (most likely those in Alaska or South America), not with local earthquakes. They gather force as they cross long ocean distances. A tsunami resulting from the 1964 Alaska earthquake caused considerable damage and ten deaths in Crescent City. There was some damage to boats and marina facilities in San Francisco Bay, where the wave height was 7.4 feet.

Devastating tsunamis have not occurred, and are not expected, in the Bay area. Because of the lack of reliable information about the kind of tsunami runups which have occurred in the past, there is considerable uncertainty over the extent of tsunami runup which could occur. The probability of a devastating tsunami is much less than the probability of a major local earthquake.

Seiches are periodic waves in closed or semi-closed bodies of water (such as the Bay). In San Francisco Bay, seiches are most likely to result from earthquakes on nearby faults. During the 1906 earthquake, there was evidence of a small seiche in the Bay. There has been no evidence of large seiches in the Bay. The maximum likely run-up from a seiche is smaller than the maximum likely run-up from a tsunami.

Possible Mitigation of Earthquake Hazards

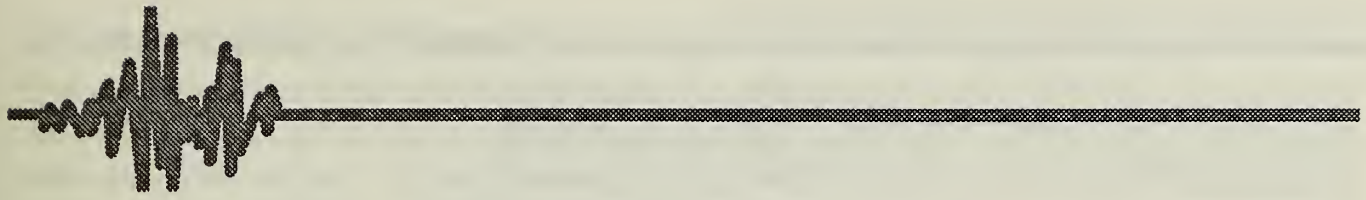
Structures vary considerably in their resistance to ground shaking. New building techniques that produce safer buildings have been incorporated into building codes over the last 60 years or so, often in response to damaging earthquakes, and especially after the 1971 San Fernando earthquake. (A more detailed discussion of the process of updating the building code will be included in the Background Report 2, Current Policies and Programs.) These techniques include improved foundation design and more effective ways of connecting structural members to withstand ground shaking and avoid collapse.

Engineers are also developing more sophisticated engineering solutions to ground shaking hazards. Seismic isolation, often called "base isolation" is a design concept based on the idea that a structure can be physically isolated from damaging earthquake ground motion. Instead of a fixed foundation, there is a system which absorbs ground motion such as blocks of laminated rubber and steel at the base of the columns. Base isolation has been used in new buildings in Japan and in California. Older buildings have been retrofitted using this system, including the Salt Lake City and County Building. While it can be very expensive, in cases where conventional seismic retrofitting is also difficult, it may be preferable. Because it often involves less interference with the above-ground structural system, it may sometimes be less destructive of the fabric of historic buildings. The Department of Public Works plans to use this technique to retrofit San Francisco's City Hall.

The sorts of techniques which can make structures less likely to collapse from ground shaking do not protect them from ground failure. Mitigation of ground failure hazards must consider the specific geologic qualities of the site, and must follow a detailed site investigation. In some circumstances, especially on large, vacant sites with relatively shallow poor soil, it can be removed and replaced with stronger engineered soil. Sometimes the soil

itself can be made more resistant to liquefaction by vibration, or mechanically compacting it by pounding it repeatedly with large weights. Vertical holes filled with crushed stone can add stiffness to surrounding soil and drain away some of the water which causes liquefaction. A stabilizing agent (or grout) can be injected into the voids of the soil to solidify it (called penetration or permeation grouting) or can be used to expand a predrilled hole to compact the surrounding soils (called displacement or compaction grouting). "Deep soil mixing" mixes a cement slurry with soil to stabilize the ground. These soil remediation techniques are often extremely expensive and disruptive. Their application depends on a wide variety of factors, including type and configuration of soils and the presence of buildings or underground utilities.

The quality and design of a structure's foundation can help protect it against ground failure. Piles or other foundation elements which extend below the poor soil can support a structure even when the soil fails. For example, during the 1906 earthquake, subsidence damaged many buildings in the vicinity of lower Market Street. Because this hazard was understood even then, the cable car conduits had been constructed on piles. After the earthquake the street (supported by poor soil) broke apart and sank up to two feet on each side of the cable car track, while the track itself (supported by piles) did not subside.



IMPACTS OF FUTURE EARTHQUAKES

Scientists generally believe that the maximum credible earthquake on the San Andreas fault (the largest that could occur) would be similar to the 1906 event, with a magnitude of about 8. However, scientists are not *expecting* a repeat of that earthquake in the near future. So much strain was released from the fault system in 1906 that an event of that magnitude is not expected to recur until about 250 years after 1906. Thus, the earthquake of greatest immediate concern on the San Andreas fault in the Bay area is the much more likely magnitude 6 or 7 on the Peninsula segment of the San Andreas fault. (See Table 2.) For planning purposes, as discussed below, many experts have used the magnitude 8.3 San Andreas event, but a smaller (but still very damaging) earthquake is much more likely to occur. Table 2 shows the relative likelihood of earthquakes of these sizes.

The maximum credible earthquake on the Hayward fault would have a magnitude of around 7. Such an earthquake is also likely to occur, as shown in Table 2.

Smaller earthquakes along these faults, with fault rupture occurring at different points along the faults, are also quite likely to occur. Their impacts will be somewhat less severe, regionally, than those estimated for the largest events, although in the area closest to the fault rupture impacts will be similar.

Because every earthquake is a unique event, and because we have experienced few recent magnitude 7 earthquakes in large

metropolitan areas in California, the estimates of casualties and damage are imprecise and are intended to be used as guides for area-wide planning and policy-making. They are not assessments of particular structures or facilities. A 1989 National Research Council panel report, *Estimating Losses from Future Earthquakes*, stated "Even using the best of today's methods and the most experienced expert opinion, losses caused by scenario earthquakes can only be estimated approximately. Overall property loss estimates are often uncertain by a factor of 2 to 3, and estimates of casualties and homeless can be uncertain by a factor of 10. Moreover, the accuracy of estimates will improve only slowly in the future, since a major source for these uncertainties is the very spareness of data on losses during actual earthquakes . . . ."

Casualties

Earthquakes' most profound impacts are deaths and serious injuries. Deaths and injuries are largely a function of the number of people in the area at the time, and the types of structures that they inhabit. Although risk is related to much more than distance from an earthquake's epicenter, it is interesting to note that about 1.26 million people live within 10 km of the likely magnitude 7 earthquake on the Northern East Bay segment of the Hayward fault. This is about 10 times the number of people at a similar distance from the epicentral region of the Loma Prieta earthquake.

Most deaths and injuries will result from the failure of structures, particularly non-ductile reinforced concrete and unreinforced masonry buildings. The number of casualties will be influenced by the time of day of the earthquake. At night more people are in relatively safe small wood-frame structures. The residential population density shown on Map 10 is a good estimate of the nighttime distribution of San Francisco's population of about 725,000. During the day more people could be in more hazardous and higher occupancy buildings, on vulnerable bridges and

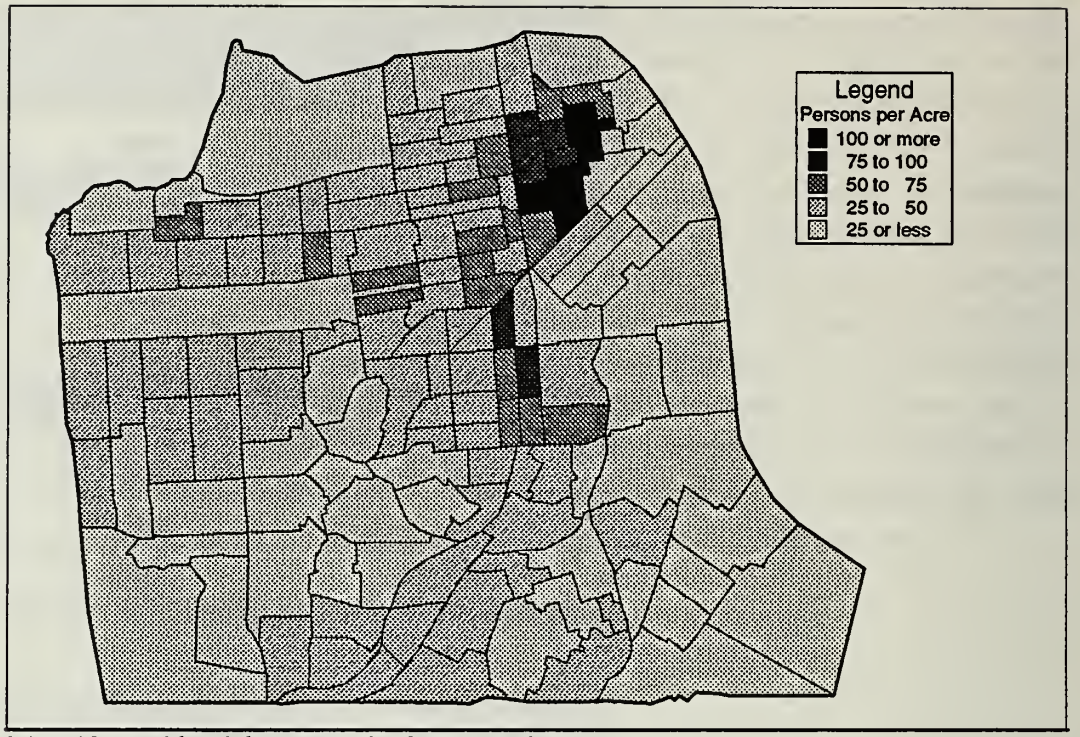
TABLE 6 - PROJECTED CASUALTIES From 8.3 San Andreas and 7.4 Hayward Earthquakes		
Event Time	**Dead**	**Hospitalized**
Northern San Andreas (M 8.3)		
2:30 a.m.	3,000	12,000
2:00 p.m.	10,000	37,000
4:30 p.m.	11,000	44,000
Hayward (M 7.4)		
2:30 a.m.	3,000	13,000
2:00 p.m.	8,000	30,000
4:30 p.m.	7,000	27,000

Source: Federal Emergency Management Agency

freeways, or on streets with falling debris. The daytime population generally consists of residents who do not leave the city for work or other reasons, commuters who enter the area for daytime work, and visitors. San Francisco's daytime population is estimated at about 1.3 million people.

In 1980, the Federal Emergency Management Agency (FEMA) estimated the likely casualties throughout the region as a result of a magnitude 8.3 earthquake on the San Andreas fault, and from a magnitude 7.4 earthquake on the Hayward fault. These estimates are shown in Table 6. FEMA estimated that, depending on the time of day, a magnitude 8.3 earthquake on the San Andreas fault could cause 3,000 to 11,000 deaths, while a magnitude 7.4 event on the Hayward fault could cause 3,000 to 8,000 deaths.

In 1987, the California Division of Mines and Geology estimated a range of 1,500-4,500 deaths from a magnitude 7.5 earthquake on the Hayward Fault. Hospitalized injuries were assumed to be about three times the number of deaths; significant non-hospitalized injuries were estimated at 30 times the number of deaths.



Map 10. Residential Density in San Francisco
Source: S.F City Planning Department and the U.S. Census 1990

As noted above, these estimates are imprecise, and could be uncertain by a factor of 10. There are important variables which could substantially change the toll. The failure (or lack of failure) of a few high-occupancy or critical facilities such as arenas, theaters, or dams will influence the final casualty count significantly. (For example, had the Cypress structure not failed, Loma Prieta casualties would have been considerably smaller; had other, similar structures collapsed there could have been many times the number of deaths.) The degree of water saturation of the ground will influence the risk of landslides and the area subject to liquefaction. Weather conditions, especially wind speed and direction, will affect the spread of fire and the ability of emergency responders to control fires.

The worst loss of life from any United States earthquake was the about 3,000 estimated deaths in the 1906 earthquake (when San Francisco's population was about 400,000). Recent urban

earthquakes in other countries, in some cases with similar building codes, have resulted in much higher casualty figures. Estimated casualties from the 1985 Mexico City earthquake (M 8.1) are up to 25,000. The 1988 Armenia earthquake (M 6.9) caused well over 25,000 fatalities, primarily from the failure of non-ductile concrete buildings.

There can be public health risks associated with natural disasters. Possible interruption of the drinking water supply and damage to the sewer system could result in the spread of disease. Large earthquakes in developed countries have not usually been accompanied by epidemics. After the 1906 earthquake there were small outbreaks of smallpox, typhoid and plague. Instructions to boil water and properly dispose of refuse were circulated through the refugee camps. Large stocks of vaccines and other medical supplies were shipped to San Francisco from elsewhere in the country. After the 1985 Mexico City earthquake there was no threat of widespread disease from contaminated water or from dead bodies. Inoculations were given as a result of public demand, not because public health professionals thought they were needed or effective. The Centers for Disease Control reviewed the disasters in which it has rendered assistance in the U.S. and elsewhere between 1970 and 1985 and concluded few had resulted in an increase in communicable disease.

Structural Damage

Most earthquake casualties result from the total or partial failure of structures, including buildings, freeways, bridges, etc. In addition to the characteristics of the earthquake and of the site (such as the magnitude, duration, soils type), the structure's characteristics including structural type, materials, design, age and quality of construction and maintenance, determine how well it will perform.

After San Francisco's 1865 earthquake, the front page of a local newspaper observed, "Well-built structures on good ground survived the shaking effects of earthquake better than structures on made ground. It is a noticeable fact that not one building having walls properly secured and lain in cement, with sound foundations, suffered by the earthquake in the least."

In order to comprehensively assess the likely damage to San Francisco's building stock from a major earthquake, we must know how many buildings, of each size and construction type, exist in different locations in San Francisco. A complete inventory of San Francisco buildings with structural information does not exist. Some studies have been done which have inventoried subsets of buildings, or have estimated of numbers of buildings. These studies are described below. They help identify areas of concern, and topics needing further study.

Figure 11. Unreinforced masonry building damaged in 1868.
Photo: San Francisco Archives, San Francisco Public Library

The 1974 Blume report assessed structural damage using 1973 information about buildings provided by the San Francisco Assessor. It uses a four category scale (slight, moderate, heavy, severe damage) to show estimated level of damage from ground shaking on a block-by-block basis for a repeat of the 1906 earthquake. The study shows slight damage in neighborhoods with a predominance of wood-frame buildings. It predicts severe damage in many downtown blocks including the South of Market, the Tenderloin, and Chinatown: areas with either higher concentrations of hazardous buildings, poor soil, or both.

Unreinforced Masonry Buildings

The Blume study also specifically examined pre-1948 masonry- or concrete-bearing-wall buildings with wood floor and roof construction, or unreinforced masonry buildings (UMBs), because of their record of poor performance in earthquakes. Large percentages of UMBs were damaged in the 1933 Long Beach earthquake, the 1971 San Fernando earthquake and the 1983 Coalinga earthquake. Eight deaths during the Loma Prieta

Map 11. Unreinforced masonry buildings in San Francisco.
Source: S.F. City Planning Department

earthquake resulted from damaged UMBs. In the Loma Prieta earthquake about 13% of all San Francisco UMBs were damaged to the extent that occupancy was limited, while about 2% of other San Francisco buildings were damaged. The Blume report recommended that the City undertake a program to reduce the hazard from UMBs through retrofit or demolition.

The City has inventoried UMBs and is now considering a program which would require retrofit. There are about 2000 UMBs in the City, and as the Blume report found, they are concentrated in the North of Market/Civic Center area (312 UMBs), Chinatown (293 UMBs), Downtown (343 UMBs), the Bush Street Corridor (196 UMBs). They are shown on Map 11. About fifteen were demolished due to damage sustained in the Loma Prieta earthquake. UMBs contain about 21,800 residential units, 70% of which are in the North of Market/Civic Center area, Chinatown, and the Bush Street Corridor. UMBs contain about 4,500 commercial enterprises, most of them relatively small. These

businesses are concentrated in the Downtown, the South of Market, Chinatown, and North of Market.

Under current policy (i.e., with no retrofit program) it is likely that approximately 530 of these 2000 buildings would be substantially damaged in a magnitude 7 earthquake on the Hayward fault, causing about 450 deaths should the earthquake occur at 3:00 p.m. or 50 deaths if it occurs at 3:00 a.m. (These casualty figures are the latest estimates, but are still imprecise. Actual figures could differ by a factor of 4.) It is likely that about 1070 of these buildings would be substantially damaged in a magnitude 8.3 earthquake on the San Andreas fault, resulting in about 1275 deaths if it occurred at 5:30 p.m.

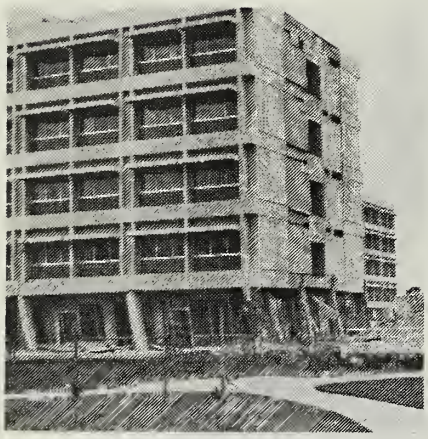


Figure 12. Non-ductile concrete building damaged in the 1971 San Fernando earthquake.
Source: Ron Gallagher, R.P. Gallagher Assoc., Inc.

Detail of building shown in Figure 12.

Other Potentially Hazardous Building Types.

There are other building types, in addition to unreinforced masonry buildings, which have not performed well in earthquakes. Buildings of these types exist in San Francisco, although they have not been inventoried. The Committee on Hazardous Buildings of the California Seismic Safety Commission, prepared a study in 1985 (*Earthquake Safety: Potentially Hazardous Buildings*) addressing this issue. A 1986 ABAG study, *Building Stock and Earthquake Losses - The San Francisco Bay Area Example*, estimated the numbers of these building types. The most serious hazard, as well as the most difficult policy issues, may be posed by non-ductile concrete frame structures. In many of these buildings, the reinforcing was not detailed or installed to allow the frame to move without fracturing. These buildings can rapidly loose strength because they lack the toughness of modern ductile concrete structures. As a result, they are susceptible to collapse in strong earthquakes. There were numerous failures of these buildings in the 1971 San Fernando earthquake. Many of the deaths in the 1985 Mexico City and 1988 Armenia earthquakes resulted from failures of non-ductile concrete frame buildings. Most of the San Francisco freeway viaducts seriously damaged in the Loma Prieta earthquake, and the Cypress viaduct which collapsed in Oakland,

Figure 13. Sequence of damage to soft-story building in Loma Prieta earthquake.
Photo: ©1989 Neil Hart

were non-ductile concrete structures. Non-ductile concrete frame buildings were constructed as factories, warehouses, or office buildings in the densest parts of the City until the San Francisco building code was changed in 1968 to require ductility. ABAG estimated that over 30% of the commercial building stock and over 50% of the industrial building stock in San Francisco is concrete. An unknown but large number of these are of non-ductile concrete. Older buildings of this type are usually from four to eight stories, although in the 1950s and 1960s some taller ones were built. Many of these buildings have historical or architectural value. Because of their larger size and central location, non-ductile concrete frame buildings are often converted to new uses such as offices or residential units. Such conversions provide opportunities to increase their seismic resistance to collapse during earthquakes.

The Committee on Hazardous Buildings described the hazards of "soft-story" buildings, those in which at least one story--often the ground floor--has significantly less rigidity and/or strength than the rest of the structure. The 1974 Blume report identified smaller wood-frame buildings with soft stories as having the potential to collapse during an earthquake. During the Loma Prieta earthquake, several soft-story buildings failed in the Marina District.

Precast concrete tilt-up buildings have been one of the most hazardous newer building types in strong earthquakes. (They are called "tilt-up" because the exterior concrete walls are formed and poured in a horizontal position and lifted and tilted into place with a crane.) The tilt-up came into general use in the early 1960s as an inexpensive industrial structure. Pre-1973 tilt-up structures with insufficient anchoring between walls and roof could collapse during an earthquake. There are relatively few of these buildings in San Francisco.

Other potential building hazards identified by the Committee on Hazardous Buildings include some pre-stressed concrete buildings; some theaters and auditoriums with long-span roof structures;

some non-structural exterior cladding and glazing and parapets. San Francisco has a program to retrofit parapets, which will be described in more detail in Background Report 2, Current Policies and Programs.

More study will be required to assess the risks posed by these other potential hazards.

Public Buildings

City-owned buildings which would be likely to fail or sustain substantial damage during an earthquake are being identified by the Department of Public Works. It is important to guarantee the functioning of some of these buildings because they house city operations (notably fire stations) which will be critical throughout the disaster period. Policy issues are also raised because the average age of San Francisco's municipal buildings is over 50 years. Many have historical or architectural value. City and County general-fund departments own almost 550 buildings. (This does not include those owned by the Unified School District, the Housing Authority, Airport, Port, Water Department.) Their replacement value is over $3.5 billion. Bond issues were approved by the voters in 1989 and 1990 to fund earthquake and safety improvements for City buildings. The bonds include funds to cover the costs of asbestos abatement, rehabilitation and repairs, and access for the disabled in conjunction with the structural work necessary for improved seismic safety.

The first stage of the City's Earthquake Safety Program is to inspect the buildings for seismic hazards. Inspected buildings were rated on a scale ranging from 1 (minor damage), 2 (moderate damage), 3 (major damage) to 4 (collapse potential). Of the first 170 buildings evaluated, (which include those expected to be most vulnerable or which contain critical functions), almost half are expected to sustain major damage or collapse in a large earthquake. These category 3 and 4 buildings include 24 Fire Department facilities, most of the Civic Center administrative

buildings, 13 branch libraries, six police facilities, and many buildings at San Francisco General and Laguna Honda Hospitals.

Planning, programming and design work is underway for 43 of these buildings. Earthquake strengthening is complete on one of them. Loss of these facilities during a major earthquake would clearly reduce the City's ability to provide emergency services during a disaster and to restore non-emergency services after the disaster. The Earthquake Safety Program work has been prioritized, with higher priority assigned to:

- facilities containing critical functions,
- unreinforced masonry buildings,
- high occupancy buildings,
- those with an ornate, monumental style of architecture which will be difficult or expensive to repair or replace when damaged,
- the severity of the seismic hazards.

The voter-approved bond issues and the Earthquake Safety Program that they fund will be described more fully in the Background Report 2, Current Policies and Programs.

Lifelines

Lifelines are physical facilities which deliver vital services to residences, commercial facilities and institutions. They include the utilities which distribute energy and water (both for consumption and fire-fighting), communications facilities, the transportation system.

The California Division of Mines and Geology (CDMG) has prepared estimates of the damage to lifelines and critical facilities which would result from major earthquakes, and the effects of damage on system performance in few days immediately following the event. *Earthquake Planning Scenario for a Magnitude 8.3 Earthquake on the San Andreas Fault in the San Francisco Bay Area* was published in 1982; *Earthquake Planning Scenario for a Magnitude 7.5 Earthquake on the Hayward Fault in the San Francisco Bay Area* was published in 1987.

Figure 14. Bay Bridge damaged in 1989 earthquake.
Photo: Bay Area Earthquake Preparedness Project

CDMG concluded that a magnitude 8.3 earthquake on the San Andreas fault will result in substantial damage to highways on the San Francisco peninsula, with vehicular movement into and out of the City impossible for many hours. The Golden Gate, Bay, Richmond and San Mateo bridges would be expected to be unusable for an extended period. While lengthy delays and detours will continue to be common, most of the initial confusion is expected to be under control within a few days. San Francisco International Airport is likely to be unusable for major airborne relief operations. Rail service will likely be unavailable. BART facilities will be damaged or will require safety inspections to an extent that the system will not function for days. Pile supported docks are likely to be available for ferry and barge operations.

After a magnitude 7.5 earthquake on the Hayward fault, the area will experience similar disruption to the transportation system. While not as impacted as those in the East Bay, many principal routes in San Francisco will be subject to major delays and detours. All trans-Bay bridges are likely to be unusable during the initial post-earthquake hours; the Bay Bridge may be closed for some time due to damage at the East Bay approaches. Other bridges, while sustaining damage at their approaches, may be usable by emergency vehicles. San Francisco International Airport is likely to be unusable for major airborne relief operations, but may be available to small aircraft and helicopters. Rail service may be available via the coast routes from southern California. BART facilities will be damaged or will require safety inspections to an

extent that the system will not function for days. The BART tunnels through the Berkeley Hills may be closed for a considerable period of time. Pile supported docks are likely to be available for ferry and barge operations.

This assessment was not based on engineering analyses of the different facilities. The actual experience during the Loma Prieta earthquake differed in some details from this pre-1989 assessment, in ways that comprehensive seismic investigations of individual facilities might have revealed. Notably, the Bay Bridge failed at one of its spans rather than at its approaches.

The CDMG concluded that a large San Andreas earthquake will probably damage electrical power plants and their ancillary facilities, resulting in a reduction in generating capacity of up to 50 per cent. The entire area may be without power, at least temporarily, during some portion of the first 72 hours. After a large Hayward fault event, about 50% of San Francisco customers may be without power for the first day, about 25% for longer. With either earthquake, the natural gas system will probably experience some breaks in major transmission lines and innumerable breaks in the local and individual systems, particularly in areas of poor soils.

Telephone communications will be hampered by overloading resulting from many calls being placed and from phones knocked off hooks.

While the aqueducts bringing water into the Bay area are likely to be damaged to some extent by a large earthquake on the San Andreas fault, the area's water storage facilities will probably contain enough water to meet demands while repairs are made. A Hayward fault earthquake will heavily damage major tunnels, aqueducts, and water distributions systems that cross the fault, resulting in possible long term water shortage. In either earthquake, local water distribution is likely to suffer disruptions, affecting water deliveries in some areas. Many areas will probably

be dependent on tanker trucks to provide water. Sewage collection systems and sewage treatment facilities located on poorer soils near the Bay are likely to suffer damage, resulting in the discharge of raw sewage into the Bay.

The Department of Public Works has commissioned a study of liquefaction and its impacts on the Municipal Water Supply System (MWSS), the Auxiliary Water Supply System (AWSS), and the sewer system, in susceptible areas, including the Marina district, Sullivan Marsh (South of Market), Mission Creek area, South Beach area, the Embarcadero waterfront, and the Telegraph Hill/North Beach area. (The MWSS is the City's basic water system, supplying potable water for homes and businesses and is generally used for fire fighting. The AWSS is a separate, redundant water system designed specifically to provide water for firefighting when the MWSS is damaged.) The study includes an inventory of these underground utilities, an evaluation of damage from a magnitude 8.3 earthquake, and a discussion of mitigation measures.

The Marina district and Sullivan Marsh portions of the study are complete. (Other portions are forthcoming.) It estimates that the MWSS will suffer about 80 breaks in the 40,000 feet of mains in the Marina district, and about 202 breaks in the 62,000 feet in Sullivan Marsh. This will result in the MWSS system being inoperable in these areas, and if the damage was not quickly controlled, could drain the University Mound Reservoir which serves other parts of the City in addition to these areas. The AWSS is expected to experience about 10 breaks in the 8,000 feet of mains in the Marina district and about 80 breaks in the 27,000 feet of mains in Sullivan Marsh. As a result, the AWSS in these two areas will likely be inoperable until breaks are located and isolated. As a consequence of the damage to the MWSS and the AWSS all fire hydrants in these areas could be inoperable and the Fire Department would have to rely on the Portable Water Supply System (PWSS), buried cisterns, and the remainder of the AWSS to fight fires. The PWSS is a system of portable large diameter hose, connections, and pumps intended to bridge breaks in the underground systems and

to access lake, bay and cistern water when water from the MWSS and AWSS are not accessible. 151 underground cisterns, with an average capacity of 75,000 gallons, were built throughout the city after 1906. The Fire Department is currently constructing about 25 more. A system of 33 Bay water suction devices is currently planned. They will provide water for firefighting in the Marina and around the perimeter of the Bay.

It is likely that as a result of a magnitude 8.3 earthquake, approximately 14,600 feet of sewers in the Marina and 15,000 feet in Sullivan Marsh will have to be replaced at a cost of approximately $17 million dollars. Collapsed sewers may cause overflows into the streets.

Large above-ground reservoirs and elevated tanks can pose a hazard during a major earthquake. Were they to fail, released water would cause damage and might endanger human life in downstream areas. The Blume report identifies inundation areas for the seven San Francisco reservoirs in these categories. That report concluded that construction procedures and review requirements provide an adequate factor of safety against reservoir failure. San Francisco reservoirs are regulated by the California Department of Water Resources, Division of Safety of Dams (DSOD), which sets structural standards. Dams and embankments are inspected by the DSOD once or twice annually. They are monitored monthly by the San Francisco Water Department for leakage and movement or settlement of embankments. Neither of these agencies believes that San Francisco reservoirs pose a serious risk to downstream populations.

Release of Hazardous Materials

Homes, businesses and other facilities contain many materials which, if not properly handled, can result in risks to life, health, or the environment. During a large earthquake such materials could be accidentally released. The Association of Bay Area Governments (ABAG) has conducted a study of the risks posed by

hazardous materials during earthquake, which resulted in their 1990 publication, *Hazardous Materials Problems in Earthquakes: A Guide to their Cause and Mitigation*. That study is summarized here. Hazardous materials releases during an earthquake can result from:

- Structural failure, where the structure collapses onto areas containing hazardous materials, including tanks, cylinders, storage or piping. Even if the hazardous material does not pose an immediate threat, it will need to be identified and mitigated before the building can be demolished.

- Dislodging of asbestos from damaged buildings.

- Pipeline breaks. Natural gas leaks are the most common release during earthquakes because of the widespread gas distribution system, and the vulnerability of underground pipelines to soil movement. Aboveground pipeline leaks may also result from differential movement between pipes, tanks and structures, impact from other structures or equipment, or damage from failing pipe supports.

- Tanks storing hazardous materials may be vulnerable. Large cylindrical tanks can fail when the contents slosh in response to horizontal movement. Unanchored tanks may topple, aboveground and underground tanks may lose their connection to pipelines, material may slosh from open-topped tanks. Damage to underground fuel tanks and their connectors could lead to ground water contamination or leakage into basements.

- Gas cylinders could be punctured, or their seals damaged, resulting in leaks.

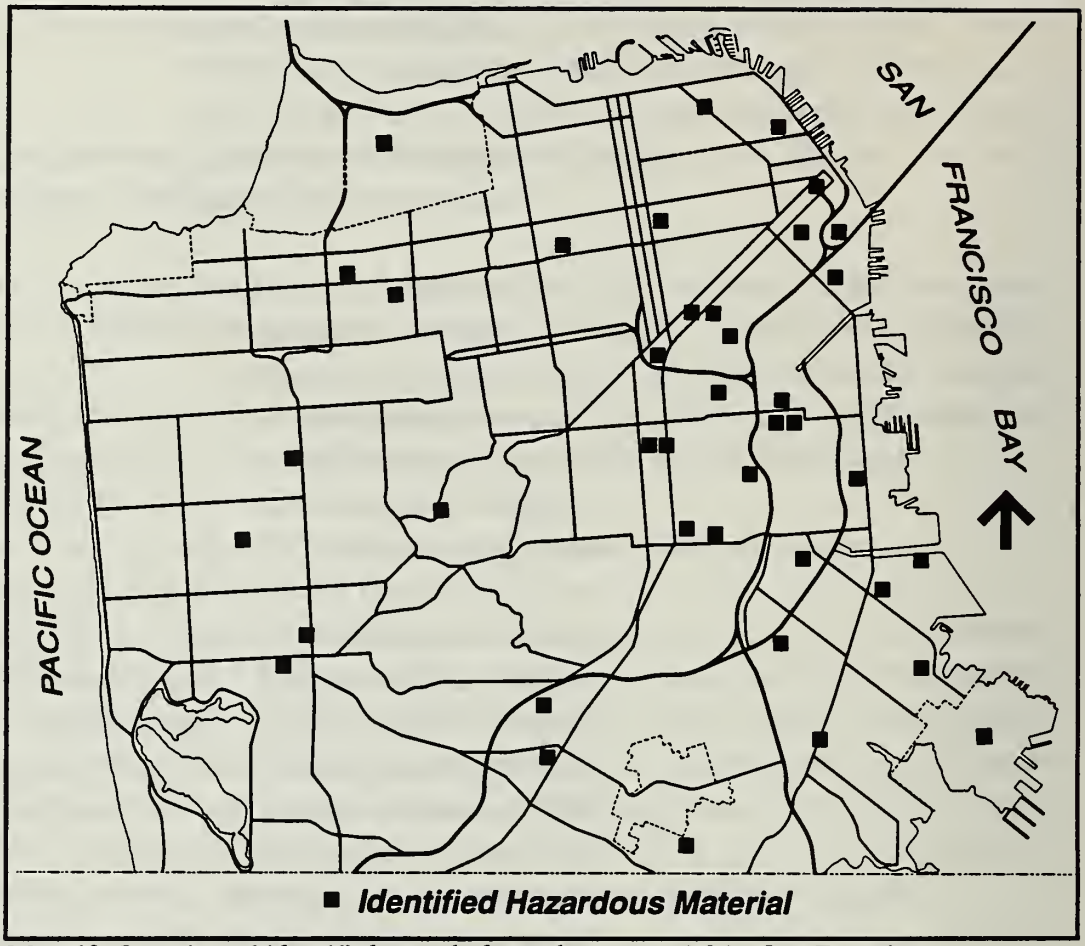
- Non-structural damage, such as falling shelves or cabinets in hospitals, laboratories, retail stores, and many other facilities

(including homes) can result in the release of hazardous materials.

- Transportation accidents involving trucks or trains carrying hazardous materials may lead to releases.

- The loss of power can effect the storage of hazardous materials, especially those under compression.

The materials which generally pose the greatest hazard during a disaster are those which can, in the form of gas, spread throughout a neighborhood and affect large numbers of people, those which are highly flammable or explosive, and those which are highly toxic or are strong irritants. These types of materials are classified as "acutely hazardous materials" in the California Health and Safety Code Chapter 6.95. As required by that chapter, the San Francisco Department of Public Health is in the process of mapping the locations of acutely hazardous materials throughout the City, and the nearby "sensitive receptors" (schools, group care facilities, medical facilities). See Map 12. These maps are based on Hazardous Materials permits and other information known to the Department of Public Health. They are revised as the Department receives new information. They show that acutely hazardous materials are located in all areas of the City, although they are somewhat concentrated in the South of Market, the Mission District, the Central Waterfront, and Bayview-Hunters Point. The materials include ammonia, sulfuric acid, chlorine and sodium cyanide. Other hazardous materials exist in areas which are not under the jurisdiction of the San Francisco Department of Public Health, including federal facilities at the Presidio and Hunters Point, and at universities and hospitals run by agencies of the State of California.



Map 12. Location of identified acutely hazardous material in San Francisco.
Source: S.F. Public Health Department

Large earthquakes both lead to release of hazardous materials and reduce the ability of emergency personnel to respond. The number of incidents requiring action will undoubtedly exceed the resources available. Transportation, utility and communication systems needed for response will be disrupted.

During the Loma Prieta earthquake, 300 spills of hazardous materials in industrial and commercial facilities were reported to authorities in the region, caused by ruptured tanks, cracked or broken pipes, leaks in equipment, and broken bottles and cans. Relatively few resulted in untreated material reaching storm drains or sewer lines. Many additional spills occurred in laboratories and plating shops and were not reported to authorities. Over 80

buildings were closed, in part, at least temporarily, for asbestos remediation.

Fire

A 1987 study prepared for the All-Industry Research Advisory Council (an association of insurers), *Fire Following Earthquake, Estimates of the Conflagration Risk to Insured Property in Greater Los Angeles and San Francisco,* assessed the likely damages of the fires which would occur after a repeat of the 1906 earthquake, a magnitude 8.3 event on the northern San Andreas fault. The study took into account ground shaking intensity, liquefaction potential, building density, building materials, the post earthquake condition of buildings, wind speed, average fire-break width, water supply functionality, and available firefighting resources. Fires were measured in SFEDs (Single Family Equivalent Dwellings). Each SFED represents 1,500 square feet of building area.

The study concluded that under rather favorable conditions (light winds, average number of fires ignited, quick reporting of fires, and road conditions permitting vehicles to travel 15 miles per hour) the entire Bay region could experience about 570 fires requiring professional firefighters. About 160 of the fires would be large fires which could not be controlled by one engine. San Francisco would experience about ten large fires: nine of about 1,000 SFED, spread throughout the City, and one (in the downtown) of about 25,000 SFED. With relatively adverse conditions (winds 20 mph or more, 20% more fires ignited) the entire Bay region would experience about 680 fires. San Francisco would have about 15 large fires: 13 of about 1,000 SFED (spread throughout the City), and one each (both in the greater downtown) of 10,000 SFED and 25,000 SFED.

Under the most favorable conditions, fire losses in San Francisco would be about $2.5 billion, or 6% of the value of all property.

Under more adverse conditions losses would be about $5.4 billion, or 13.3% of all property values.

The study's author noted the Fire Department's plans to extend San Francisco's Auxiliary Water Supply System (AWSS) and to create a Portable Water Supply System (PWSS) and stated that the "implementation of these plans will significantly increase the post-earthquake capabilities of the department and probably will decrease losses in San Francisco due to fire following earthquake." (See the section on Lifelines, above, for a brief description of the AWSS and the PWSS.) The AWSS is concentrated in the parts of the City which were the most densely built when the system was planned immediately after the 1906 earthquake and fire. Extensions are planned in the areas in the west and south parts of the City which are not well served by the current system. An AWSS extension along Third Street is currently under construction. Additional extensions in the Bayview/Hunters Point, West Portal, Mission, and Ocean Avenue areas are planned. The PWSS has been implemented, and was used during the 1989 earthquake and the 1991 East Bay Hills fire. Consequently it is reasonable to expect fire damage to be less than was estimated in 1987.

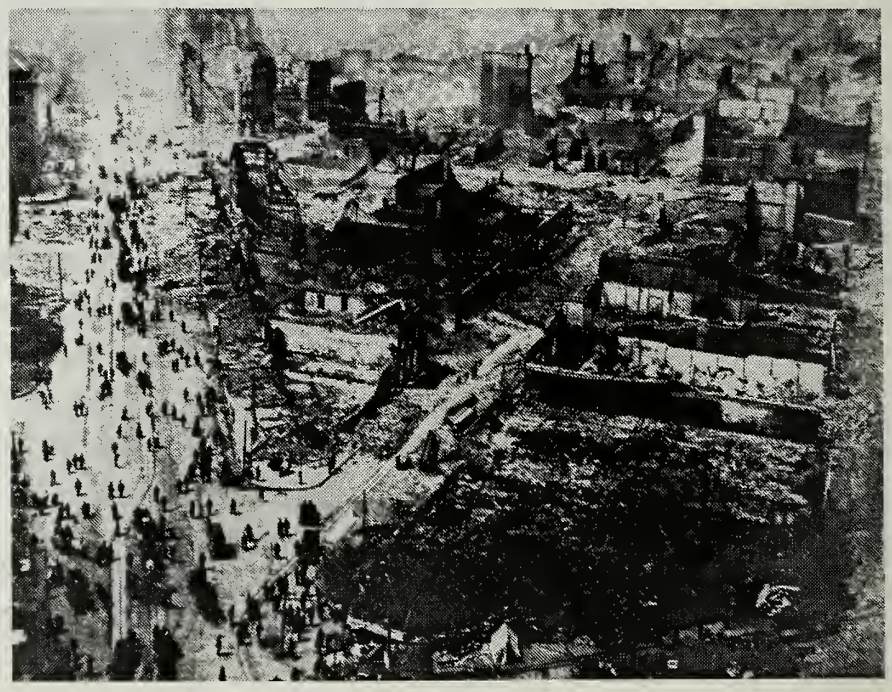


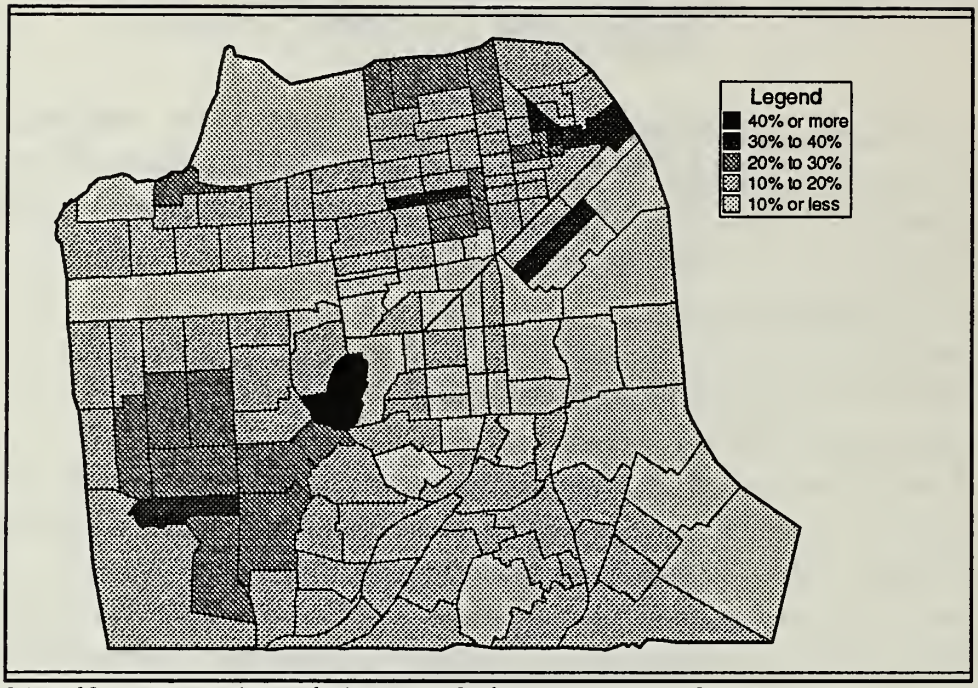
Figure 15. 1906 fire destruction.
Photo: San Francisco Archives, San Francisco Public Library

Social and Economic Impacts

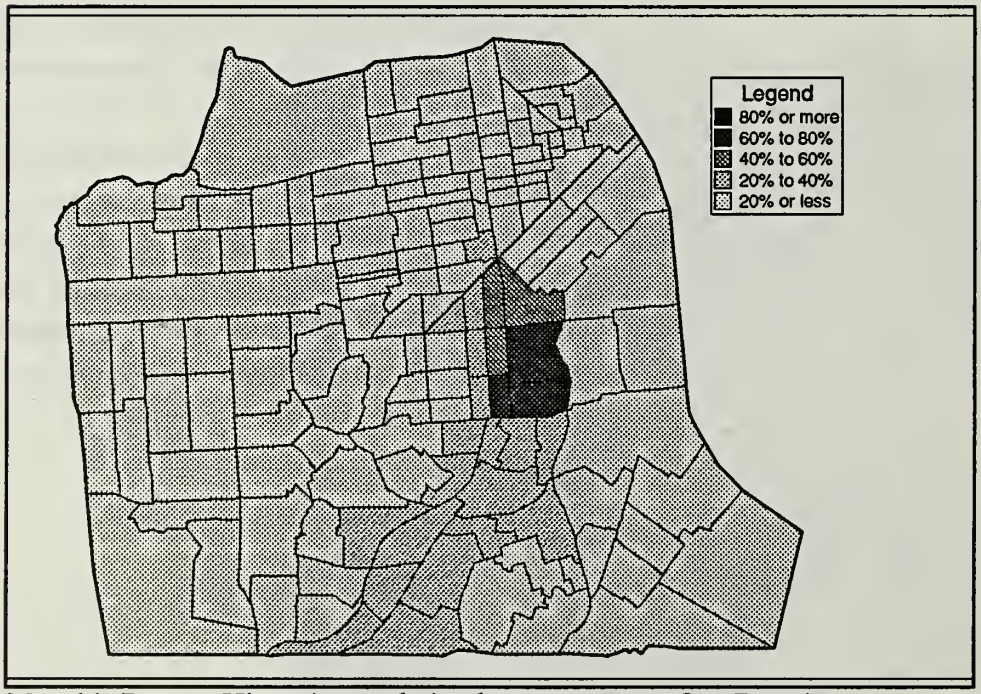
Most earthquake impact research has concerned damage to buildings and infrastructure, and the resulting deaths and injuries. There will be other, less easily quantified, but still significant, losses from a major earthquake.

Vulnerable Populations

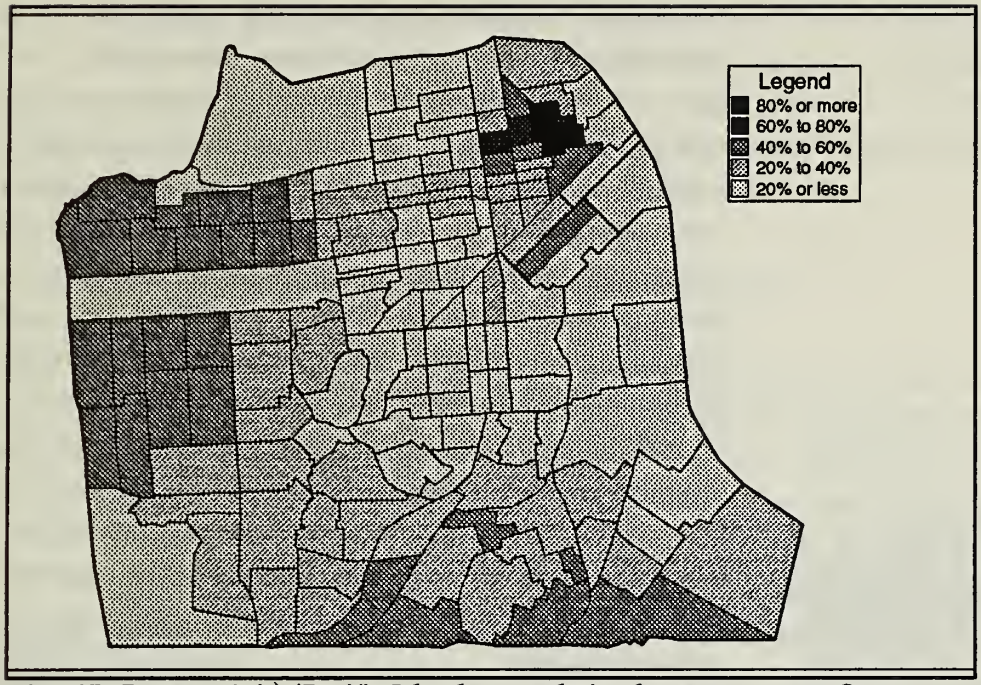
Risk of death, injury or displacement as a result of an earthquake is not evenly distributed. As discussed above, some geographical areas and some types of buildings are more vulnerable to earthquake damage. Some people and some population groups are also more vulnerable, regardless of where they live. People who cannot walk easily or have other disabilities may have difficulty negotiating damaged buildings or sidewalks. Those who do not understand English well may not receive important safety information before, during, and after a disaster. Map 13 shows the areas with a higher concentration of people over 65 years old, who may have a greater likelihood of being disabled. Maps 14 and 15 show areas with a higher concentration of those who may be likely to speak a language other than English. People with low incomes are more likely to live in buildings, such as unreinforced masonry buildings, which are vulnerable to earthquake damage. They may also be less likely to have stored materials and equipment (such as flashlights and extra food) which will be needed after a disaster, or the financial resources to see them through temporary or long-term displacement or unemployment because of an earthquake.



Map 13. Percent of population over 65 by census tract, San Francisco.
Source: S.F. City Planning Department and U.S. Census 1990.



Map 14. Percent Hispanic population by census tract, San Francisco.
Source: S.F. City Planning Department and U.S. Census 1990



Map 15. Percent Asian/Pacific Islander population by census tract, San Francisco.
Source: S.F. City Planning Department and U.S. Census 1990.

Loss of housing

Damage to buildings during an earthquake has impacts beyond the immediate life safety concerns and the monetary losses suffered by private and public owners of damaged buildings, and building tenants. When buildings are destroyed, damaged, or unusable because of a lack of utilities, their residents will be homeless. This is an especially important issue in San Francisco because of the scarcity of housing, particularly low-cost housing, even in the absence of a major earthquake. Homelessness and displacement as a result of an earthquake can take many forms. Some housing units will be lost forever; the buildings will be destroyed or damaged to the extent that they cannot be repaired. Some units will be repairable, but will not be inhabitable for an extended time while the work is carried out. Some units may not be structurally damaged, but will be without services for some time.

Figure 16. Refugees living in Jefferson Square, 1906.
Photo: Bancroft Archives, Bay Area Earthquake Preparedness Project

Techniques for estimating building losses can be extended to estimate the number of homeless households. A model for estimating homelessness using the Los Angeles area as an example was published in 1986, *Estimating of Homeless Caseload for Disaster Assistance Due to an Earthquake.* Numbers of homeless households were estimated along with the location and type of housing from which they were displaced, leading to conclusions about their status as owners/renters, income, age. The study concluded that about 116,000 Southern California households will need some kind of housing assistance. In the hardest-hit counties 5 to 8% of the households will be homeless. Because dwellings in multiple-unit buildings, older buildings and unreinforced masonry buildings are more likely to be lost, renters, low-income people and the elderly are more likely to lose their homes in an earthquake. It is reasonable to expect that these general tendencies will also occur in San Francisco.

ABAG, with funding from the Red Cross and BAREPP, is currently conducting a study to estimate the number of housing units in the Bay Area which will be made uninhabitable in future earthquakes. The results will be available in 1992.

Building Loss Issues for Businesses

Small businesses may be more vulnerable to earthquakes than larger businesses. They are more likely to be located in potentially hazardous buildings. The Department of City Planning's study of unreinforced masonry buildings (UMBs) showed that they contain about 4500 commercial enterprises, most of them in the Downtown, South of Market, Chinatown and North of Market areas. These businesses provide about 46,000 jobs, and provide needed goods and services in these neighborhoods. These kinds of establishments may have less business flexibility than larger businesses, and less ability to survive the economic disruption of a disaster. They have little capital, and are less likely to have alternative business locations.

In addition to loss of buildings, inventory and equipment, business will lose important business-related records and other information. They may suffer a loss of work because of difficulties felt by suppliers, customers or employees. Access to businesses not directly impacted may be difficult.

Impact on Historic Resources

Older buildings are among those most vulnerable to destruction or heavy damage from a large earthquake. Much of the City as we now know it resulted from the rebuilding of damaged or destroyed buildings after the 1906 earthquake. Some older buildings do not have the more recent engineering features which make buildings more resistant to ground shaking. Because of the history of San Francisco, the areas near the Bay and the historic Bay inlets were among the first parts of the City to be settled and still contain important historic resources, as well as the most severe ground failure hazards. The part of the City most vulnerable to fire, the dense downtown area, also contains many historic buildings and other structures.

Figure 17. Hibernia Bank Building damaged in 1906.
Photo: Bancroft Archives, Bay Area Earthquake Preparedness Project

The Environmental Impact Report (EIR) on the UMB program shows that San Francisco UMBs have considerable historic value. Ninety-nine percent of the approximately 2000 UMBs were built before 1933. Forty-two are San Francisco landmarks, representing about 20% of the City's landmarks. Many others are located in historic districts or conservation districts. The EIR found that a magnitude 7 Hayward fault earthquake would be likely to result in damage greater than 40% of the replacement cost to about 530 (27%) of the City's UMBs. A magnitude 8.3 San Andreas earthquake would result in this level of damage to about 1070 (53%) of the UMBs.

We do not have similar analyses of earthquake damage to other historic resources, but it is reasonable to expect that a large earthquake will result in a serious and irreplaceable loss of the historic fabric of San Francisco.

Macroeconomic Impacts

Direct damage to structures and lifelines will endanger people, their homes, and the historic fabric of the City, as well as represent a substantial economic loss. It is estimated that the structural damage to private and public facilities in the Loma Prieta earthquake resulted in a cost of about $6 billion dollars to the region. In 1980, FEMA estimated that a magnitude 8.3 earthquake on the San Andreas fault could result in $38 billion worth of property damage, and that a large Hayward fault earthquake could result in $44 billion damage. These estimates include private and public buildings, but do not include transportation and communications facilities, dams, utilities installations and special purpose structures.

Figure 18. Loss of transportation access after Loma Prieta.
Photo: ©1991 Neil Hart

In addition to structural damage, considerable personal and business property will be damaged. Building contents will be destroyed and damaged. Many vehicles will be destroyed. Businesses, even those whose buildings are not destroyed, may be severely disrupted by power and communications interruptions and transportation difficulties they, their customers and their suppliers experience. Unemployment is likely to result from business disruption. Shortages of building materials, architects, engineers, contractors may raise reconstruction costs, both for homes and businesses.

After a major disaster, considerable financial resources, in the form of grants and loans, from outside of the region become available. These programs are intended to assist in an economic recovery. They will not, however, totally cover the costs of repairs, reconstruction and recovery.

Some, but not most, of the economic losses will be covered by insurance. About 15% to 20% of property is insured for shaking losses; almost all is insured for fire. Damage to vehicles is likely to be insured. Many injuries may be covered by health or workers

compensation policies. About one-third of commercial property insurance policies contain coverage for business interruption losses.

The Association of Bay Area Governments (ABAG) has prepared a study of the macroeconomic impacts of the Loma Prieta earthquake. It examines trends in retail sales, unemployment claims, and other indicators of regional economic conditions in the Bay Area, Santa Cruz, Monterey, and San Benito counties.

The study estimates that about 7,100 workers in the region who were eligible for unemployment assistance were laid off as a result of the earthquake. These earthquake-related employment impacts lasted about four months. The permanent reduction in the Gross Regional Product (GRP) was estimated at between $181 million to $725 million. These regional numbers are not large in relation to the total regional economy. These estimated losses represent considerably less than 1% of the regional employment of about 3 million, and of the 1989 GRP of $174 billion.

The economic effects were not, however, evenly spread throughout the region. Some areas were much harder hit than others, and some economic activity shifted from one county to another.

The study estimates that San Francisco experienced a loss of between $31 million and $73 million in taxable sales in the fourth quarter of 1989 (up to about 4% of the expected total), and a loss of about 1,100 jobs, largely in the retail sector, as a result of the earthquake. Some of this loss appears to be the result of a shift in retail activity to other counties in the region. The report concluded that this disproportionate loss in San Francisco was likely due to the reduction in transportation access, stressing the critical role of transportation and infrastructure in maintaining economic activity.

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